A BRIEF HISTORY OF TIME

THE UPDATED AND EXPANDED TENTH ANNIVERSARY EDITION

STEPHEN HAWKING

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ALSO BY STEPHEN HAWKING

Stephen Hawking's A Brief History of Time: A Reader's Companion

Black Holes and Baby Universes and Other Essays

The Illustrated A Brief History of Time

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C O N T E N T S

FOREWORD

I didn't write a foreword to the original edition of *A Brief History of Time*. That was done by Carl Sagan. Instead, I wrote a short piece titled "Acknowledgments" in which I was advised to thank everyone. Some of the foundations that had given me support weren't too pleased to have been mentioned, however, because it led to a great increase in applications.

I don't think anyone, my publishers, my agent, or myself, expected the book to do anything like as well as it did. It was in the London *Sunday Times* best-seller list for 237 weeks, longer than any other book (apparently, the Bible and Shakespeare aren't counted). It has been translated into something like forty languages and has sold about one copy for every 750 men, women, and children in the world. As Nathan Myhrvold of Microsoft (a former post-doc of mine) remarked: I have sold more books on physics than Madonna has on sex.

The success of *A Brief History* indicates that there is widespread interest in the big questions like: Where did we come from? And why is the universe the way it is?

I have taken the opportunity to update the book and include new theoretical and observational results obtained since the book was first published (on April Fools' Day, 1988). I have included a new chapter on wormholes and time travel. Einstein's General Theory of Relativity seems to offer the possibility that we could create and maintain wormholes, little tubes that connect different regions of space-time. If so, we might be able to use them for rapid travel around the galaxy or travel back in time. Of course, we have not seen anyone from the future (or have we?) but I discuss a possible explanation for this.

I also describe the progress that has been made recently in finding "dualities" or correspondences between apparently different theories of physics. These correspondences are a strong indication that there is a complete unified theory of physics, but they also suggest that it may not be possible to express this theory in a single fundamental formulation. Instead, we may have to use different reflections of the underlying theory in different situations. It might be like our being unable to represent the surface of the earth on a single map and having to use different maps in different regions. This would be a revolution in our view of the unification of the laws of science but it would not change the most important point: that the universe is governed by a set of rational laws that we can discover and understand.

On the observational side, by far the most important development has been the measurement of fluctuations in the cosmic microwave background radiation by COBE (the Cosmic Background Explorer satellite) and other collaborations. These fluctuations are the fingerprints of creation, tiny initial irregularities in the otherwise smooth and uniform early universe that later grew into galaxies, stars, and all the structures we see around us. Their form agrees with the predictions of the proposal that the universe has no boundaries or edges in the imaginary time direction; but further observations will be necessary to distinguish this proposal from other possible explanations for

the fluctuations in the background. However, within a few years we should know whether we can believe that we live in a universe that is completely self-contained and without beginning or end.

Stephen Hawking

CHAPTER 1

OUR PICTURE OF THE UNIVERSE

A well-known scientist (some say it was Bertrand Russell) once gave a public lecture on astronomy. He described how the earth orbits around the sun and how the sun, in turn, orbits around the center of a vast collection of stars called our galaxy. At the end of the lecture, a little old lady at the back of the room got up and said: "What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise." The scientist gave a superior smile before replying, "What is the tortoise standing on?" "You're very clever, young man, very clever," said the old lady. "But it's turtles all the way down!"

Most people would find the picture of our universe as an infinite tower of tortoises rather ridiculous, but why do we think we know better? What do we know about the universe, and how do we know it? Where did the universe come from, and where is it going? Did the universe have a beginning, and if so, what happened *before* then? What is the nature of time? Will it ever come to an end? Can we go back in time? Recent breakthroughs in physics, made possible in part by

fantastic new technologies, suggest answers to some of these longstanding questions. Someday these answers may seem as obvious to us as the earth orbiting the sun—or perhaps as ridiculous as a tower of tortoises. Only time (whatever that may be) will tell.

As long ago as 340 B.C. the Greek philosopher Aristotle, in his book *On the Heavens*, was able to put forward two good arguments for believing that the earth was a round sphere rather than a flat plate. First, he realized that eclipses of the moon were caused by the earth coming between the sun and the moon. The earth's shadow on the moon was always round, which would be true only if the earth was spherical. If the earth had been a flat disk, the shadow would have been elongated and elliptical, unless the eclipse always occurred at a time when the sun was directly under the center of the disk. Second, the Greeks knew from their travels that the North Star appeared lower in the sky when viewed in the south than it did in more northerly regions. (Since the North Star lies over the North Pole, it appears to be directly above an observer at the North Pole, but to someone looking from the equator, it appears to lie just at the horizon.) From the difference in the apparent position of the North Star in Egypt and Greece, Aristotle even quoted an estimate that the distance around the earth was 400,000 stadia. It is not known exactly what length a stadium was, but it may have been about 200 yards, which would make Aristotle's estimate about twice the currently accepted figure. The Greeks even had a third argument that the earth must be round, for why else does one first see the sails of a ship coming over the horizon, and only later see the hull?

Aristotle thought the earth was stationary and that the sun, the moon, the planets, and the stars moved in circular orbits about the earth. He believed this because he felt, for mystical reasons, that the earth was the center of the universe, and that circular motion was the most perfect. This idea was elaborated by Ptolemy in the second century A.D. into a complete cosmological model. The earth stood at the center, surrounded by eight spheres that carried the moon, the sun, the stars, and the five planets known at the time, Mercury, Venus,

Mars, Jupiter, and Saturn (Fig. 1.1). The planets themselves moved on smaller circles attached to their respective spheres in order to account for their rather complicated observed paths in the sky. The outermost sphere carried the so-called fixed stars, which always stay in the same positions relative to each other but which rotate together across the sky. What lay beyond the last sphere was never made very clear, but it certainly was not part of mankind's observable universe.

Ptolemy's model provided a reasonably accurate system for predicting the positions of heavenly bodies in the sky. But in order to predict these positions correctly, Ptolemy had to make an assumption that the moon followed a path that sometimes brought it twice as close to the earth as at other times. And that meant that the moon ought sometimes to appear twice as big as at other times! Ptolemy recognized this flaw, but nevertheless his model was generally, although not universally, accepted. It was adopted by the Christian church as the picture of the universe that was in accordance with Scripture, for it had the great

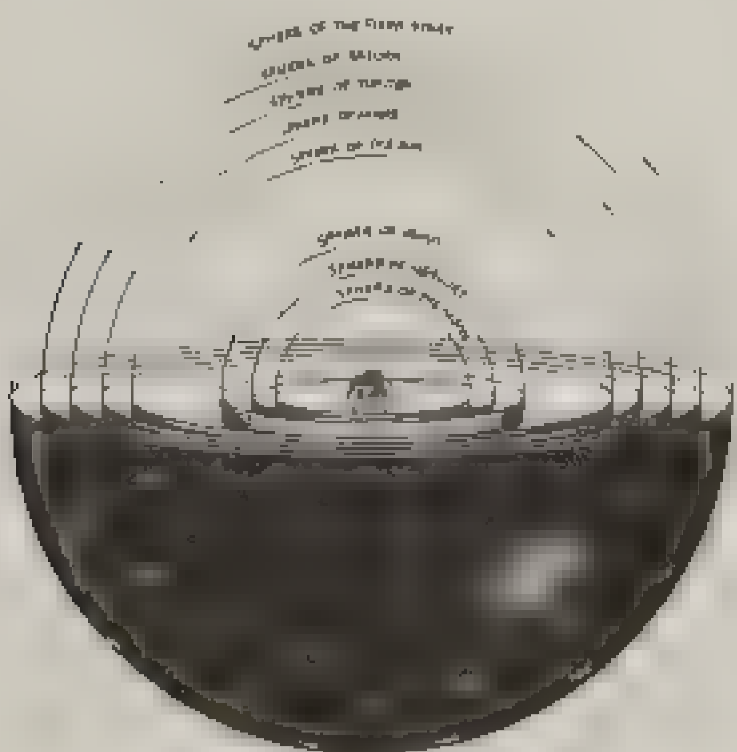

FIGURE 1.1

advantage that it left room outside the sphere of fixed stars for heaven and hell.

A simpler model, however, was proposed in 1514 by a Polish priest, Nicholas Copernicus. (At first, perhaps for fear of being branded a heretic by his church, Copernicus circulated his model anonymously.) His idea was that the sun was stationary at the center and that the earth and the planets moved in circular orbits around the sun. Nearly a century passed before this idea was taken seriously. Then two astronomers—the German, Johannes Kepler, and the Italian, Galileo Galilei—started publicly to support the Copernican theory, despite the fact that the orbits it predicted did not quite match the ones observed. The death blow to the Aristotelian/Ptolemaic theory came in 1609. In that year, Galileo started observing the night sky with a telescope, which had just been invented. When he looked at the planet Jupiter, Galileo found that it was accompanied by several small satellites or moons that orbited around it. This implied that everything did not have to orbit directly around the earth, as Aristotle and Ptolemy had thought. (It was, of course, still possible to believe that the earth was stationary at the center of the universe and that the moons of Jupiter moved on extremely complicated paths around the earth, giving the appearance that they orbited Jupiter. However, Copernicus's theory was much simpler.) At the same time, Johannes Kepler had modified Copernicus's theory, suggesting that the planets moved not in circles but in ellipses (an ellipse is an elongated circle). The predictions now finally matched the observations.

As far as Kepler was concerned, elliptical orbits were merely an ad hoc hypothesis, and a rather repugnant one at that, because ellipses were clearly less perfect than circles. Having discovered almost by accident that elliptical orbits fit the observations well, he could not reconcile them with his idea that the planets were made to orbit the sun by magnetic forces. An explanation was provided only much later, in 1687, when Sir Isaac Newton published his *Philosophiae Naturalis Principia Mathematica*, probably the most important single work ever

published in the physical sciences. In it Newton not only put forward a theory of how bodies move in space and time, but he also developed the complicated mathematics needed to analyze those motions. In addition, Newton postulated a law of universal gravitation according to which each body in the universe was attracted toward every other body by a force that was stronger the more massive the bodies and the closer they were to each other. It was this same force that caused objects to fall to the ground. (The story that Newton was inspired by an apple hitting his head is almost certainly apocryphal. All Newton himself ever said was that the idea of gravity came to him as he sat "in a contemplative mood" and "was occasioned by the fall of an apple.") Newton went on to show that, according to his law, gravity causes the moon to move in an elliptical orbit around the earth and causes the earth and the planets to follow elliptical paths around the sun.

The Copernican model got rid of Ptolemy's celestial spheres, and with them, the idea that the universe had a natural boundary. Since "fixed stars" did not appear to change their positions apart from a rotation across the sky caused by the earth spinning on its axis, it became natural to suppose that the fixed stars were objects like our sun but very much farther away.

Newton realized that, according to his theory of gravity, the stars should attract each other, so it seemed they could not remain essentially motionless. Would they not all fall together at some point? In a letter in 1691 to Richard Bentley, another leading thinker of his day, Newton argued that this would indeed happen if there were only a finite number of stars distributed over a finite region of space. But he reasoned that if, on the other hand, there were an infinite number of stars, distributed more or less uniformly over infinite space, this would not happen, because there would not be any central point for them to fall to.

This argument is an instance of the pitfalls that you can encounter in talking about infinity. In an infinite universe, every point can be regarded as the center, because every point has an infinite number of

stars on each side of it. The correct approach, it was realized only much later, is to consider the finite situation, in which the stars all fall in on each other, and then to ask how things change if one adds more stars roughly uniformly distributed outside this region. According to Newton's law, the extra stars would make no difference at all to the original ones on average, so the stars would fall in just as fast. We can add as many stars as we like, but they will still always collapse in on themselves. We now know it is impossible to have an infinite static model of the universe in which gravity is always attractive.

It is an interesting reflection on the general climate of thought before the twentieth century that no one had suggested that the universe was expanding or contracting. It was generally accepted that either the universe had existed forever in an unchanging state, or that it had been created at a finite time in the past more or less as we observe it today. In part this may have been due to people's tendency to believe in eternal truths, as well as the comfort they found in the thought that even though they may grow old and die, the universe is eternal and unchanging.

Even those who realized that Newton's theory of gravity showed that the universe could not be static did not think to suggest that it might be expanding. Instead, they attempted to modify the theory by making the gravitational force repulsive at very large distances. This did not significantly affect their predictions of the motions of the planets, but it allowed an infinite distribution of stars to remain in equilibrium—with the attractive forces between nearby stars balanced by the repulsive forces from those that were farther away. However, we now believe such an equilibrium would be unstable: if the stars in some region got only slightly nearer each other, the attractive forces between them would become stronger and dominate over the repulsive forces so that the stars would continue to fall toward each other. On the other hand, if the stars got a bit farther away from each other, the repulsive forces would dominate and drive them farther apart.

Another objection to an infinite static universe is normally ascribed

the German philosopher Heinrich Olbers, who wrote about this theory in 1823. In fact, various contemporaries of Newton had raised the problem, and the Olbers article was not even the first to contain plausible arguments against it. It was, however, the first to be widely noted. The difficulty is that in an infinite static universe nearly every line of sight would end on the surface of a star. Thus one would expect that the whole sky would be as bright as the sun, even at night. Olbers's counter-argument was that the light from distant stars would be dimmed by absorption by intervening matter. However, if that happened the intervening matter would eventually heat up until it glowed as brightly as the stars. The only way of avoiding the conclusion that the whole of the night sky should be as bright as the surface of the sun would be to assume that the stars had not been shining forever but had turned on at some finite time in the past. In that case the absorbing matter might not have heated up yet or the light from distant stars might not yet have reached us. And that brings us to the question of what could have caused the stars to have turned on in the first place.

The beginning of the universe had, of course, been discussed long before this. According to a number of early cosmologies and the Jewish/Christian/Muslim tradition, the universe started at a finite, and not very distant, time in the past. One argument for such a beginning was the feeling that it was necessary to have "First Cause" to explain the existence of the universe. (Within the universe, you always explained one event as being caused by some earlier event, but the existence of the universe itself could be explained in this way only if it had some beginning.) Another argument was put forward by St. Augustine in his book *The City of God*. He pointed out that civilization is progressing and we remember who performed this deed or developed that technique. Thus man, and so also perhaps the universe, could not have been around all that long. St. Augustine accepted a date of about 5000 B.C. for the Creation of the universe according to the book of Genesis. (It is interesting that this is not so far from the end of the

last Ice Age about 10,000 B.C., which is when archaeologists tell us that civilization really began.)

Aristotle, and most of the other Greek philosophers, on the other hand, did not like the idea of a creation because it smacked too much of divine intervention. They believed, therefore, that the human race and the world around it had existed, and would exist, forever. The ancients had already considered the argument about progress described above, and answered it by saying that there had been periodic floods or other disasters that repeatedly set the human race right back to the beginning of civilization.

The questions of whether the universe had a beginning in time and whether it is limited in space were later extensively examined by the philosopher Immanuel Kant in his monumental (and very obscure) work *Critique of Pure Reason*, published in 1781. He called these questions antinomies (that is, contradictions) of pure reason because he felt that there were equally compelling arguments for believing the thesis, that the universe had a beginning, and the antithesis, that it had existed forever. His argument for the thesis was that if the universe did not have a beginning, there would be an infinite period of time before any event, which he considered absurd. The argument for the antithesis was that if the universe had a beginning, there would be an infinite period of time before it, so why should the universe begin at any one particular time? In fact, his cases for both the thesis and the antithesis are really the same argument. They are both based on his unspoken assumption that time continues back forever, whether or not the universe had existed forever. As we shall see, the concept of time has no meaning before the beginning of the universe. This was first pointed out by St. Augustine. When asked: "What did God do before he created the universe?" Augustine didn't reply: "He was preparing Hell for people who asked such questions." Instead, he said that time was a property of the universe that God created, and that time did not exist before the beginning of the universe.

When most people believed in an essentially static and unchanging

universe, the question of whether or not it had a beginning was really one of metaphysics or theology. One could account for what was observed equally well on the theory that the universe had existed forever or on the theory that it was set in motion at some finite time in such a manner as to look as though it had existed forever. But in 1929, Edwin Hubble made the landmark observation that wherever you look, distant galaxies are moving rapidly away from us. In other words, the universe is expanding. This means that at earlier times objects would have been closer together. In fact, it seemed that there was a time, about ten or twenty thousand million years ago, when they were all at exactly the same place and when, therefore, the density of the universe was infinite. This discovery finally brought the question of the beginning of the universe into the realm of science.

Hubble's observations suggested that there was a time, called the big bang, when the universe was infinitesimally small and infinitely dense. Under such conditions all the laws of science, and therefore all ability to predict the future, would break down. If there were events earlier than this time, then they could not affect what happens at the present time. Their existence can be ignored because it would have no observational consequences. One may say that time had a beginning at the big bang, in the sense that earlier times simply would not be defined. It should be emphasized that this beginning in time is very different from those that had been considered previously. In an unchanging universe a beginning in time is something that has to be imposed by some being outside the universe; there is no physical necessity for a beginning. One can imagine that God created the universe at literally any time in the past. On the other hand, if the universe is expanding, there may be physical reasons why there had to be a beginning. One could still imagine that God created the universe at the instant of the big bang, or even afterwards in just such a way as to make it look as though there had been a big bang, but it would be meaningless to suppose that it was created before the big bang. An expanding universe does not preclude a creator, but it does place limits on when he might have carried out his job!

In order to talk about the nature of the universe and to discuss questions such as whether it has a beginning or an end, you have to be clear about what a scientific theory is. I shall take the simpleminded view that a theory is just a model of the universe, or a restricted part of it, and a set of rules that relate quantities in the model to observations that we make. It exists only in our minds and does not have any other reality (whatever that might mean). A theory is a good theory if it satisfies two requirements: It must accurately describe a large class of observations on the basis of a model that contains only a few arbitrary elements, and it must make definite predictions about the results of future observations. For example, Aristotle believed Empedocles's theory that everything was made out of four elements, earth, air, fire, and water. This was simple enough, but did not make any definite predictions. On the other hand, Newton's theory of gravity was based on an even simpler model, in which bodies attracted each other with a force that was proportional to a quantity called their mass and inversely proportional to the square of the distance between them. Yet it predicts the motions of the sun, the moon, and the planets to a high degree of accuracy.

Any physical theory is always provisional, in the sense that it is only a hypothesis: you can never prove it. No matter how many times the results of experiments agree with some theory, you can never be sure that the next time the result will not contradict the theory. On the other hand, you can disprove a theory by finding even a single observation that disagrees with the predictions of the theory. As philosopher of science Karl Popper has emphasized, a good theory is characterized by the fact that it makes a number of predictions that could in principle be disproved or falsified by observation. Each time new experiments are observed to agree with the predictions the theory survives, and our confidence in it is increased; but if ever a new observation is found to disagree, we have to abandon or modify the theory.

At least that is what is supposed to happen, but you can always question the competence of the person who carried out the observation.

In practice, what often happens is that a new theory is devised that is

really an extension of the previous theory. For example, very accurate observations of the planet Mercury revealed a small difference between its motion and the predictions of Newton's theory of gravity. Einstein's general theory of relativity predicted a slightly different motion from Newton's theory. The fact that Einstein's predictions matched what was seen, while Newton's did not, was one of the crucial confirmations of the new theory. However, we still use Newton's theory for all practical purposes because the difference between its predictions and those of general relativity is very small in the situations that we normally deal with. Newton's theory also has the great advantage that it is much simpler to work with than Einstein's!

The eventual goal of science is to provide a single theory that describes the whole universe. However, the approach most scientists actually follow is to separate the problem into two parts. First, there are the laws that tell us how the universe changes with time. If we know what the universe is like at any one time, these physical laws tell us how it will look at any later time. Second, there is the question of the initial state of the universe. Some people feel that science should be concerned with only the first part; they regard the question of the initial situation as a matter for metaphysics or religion. They would say that God, being omnipotent, could have started the universe off any way he wanted. That may be so, but in that case he also could have made it develop in a completely arbitrary way. Yet it appears that he chose to make it evolve in a very regular way according to certain laws. It therefore seems equally reasonable to suppose that there are also laws governing the initial state.

It turns out to be very difficult to devise a theory to describe the universe all in one go. Instead, we break the problem up into bits and invent a number of partial theories. Each of these partial theories describes and predicts a certain limited class of observations, neglecting the effects of other quantities, or representing them by simple sets of numbers. It may be that this approach is completely wrong. If everything in the universe depends on everything else in a fundamental way,

it might be impossible to get close to a full solution by investigating parts of the problem in isolation. Nevertheless, it is certainly the way that we have made progress in the past. The classic example again is the Newtonian theory of gravity, which tells us that the gravitational force between two bodies depends only on one number associated with each body, its mass, but is otherwise independent of what the bodies are made of. Thus one does not need to have a theory of the structure and constitution of the sun and the planets in order to calculate their orbits.

Today scientists describe the universe in terms of two basic partial theories—the general theory of relativity and quantum mechanics. They are the great intellectual achievements of the first half of this century. The general theory of relativity describes the force of gravity and the large-scale structure of the universe, that is, the structure on scales from only a few miles to as large as a million million million million (1 with twenty-four zeros after it) miles, the size of the observable universe. Quantum mechanics, on the other hand, deals with phenomena on extremely small scales, such as a millionth of a millionth of an inch. Unfortunately, however, these two theories are known to be inconsistent with each other—they cannot both be correct. One of the major endeavors in physics today, and the major theme of this book, is the search for a new theory that will incorporate them both—a quantum theory of gravity. We do not yet have such a theory, and we may still be a long way from having one, but we do already know many of the properties that it must have. And we shall see, in later chapters, that we already know a fair amount about the predictions a quantum theory of gravity must make.

Now, if you believe that the universe is not arbitrary, but is governed by definite laws, you ultimately have to combine the partial theories into a complete unified theory that will describe everything in the universe. But there is a fundamental paradox in the search for such a complete unified theory. The ideas about scientific theories outlined above assume we are rational beings who are free to observe the universe as we want and to draw logical deductions from what we see.

In such a scheme it is reasonable to suppose that we might progress ever closer toward the laws that govern our universe. Yet if there really is a complete unified theory, it would also presumably determine our actions. And so the theory itself would determine the outcome of our search for it! And why should it determine that we come to the right conclusions from the evidence? Might it not equally well determine that we draw the wrong conclusion? Or no conclusion at all?

The only answer that I can give to this problem is based on Darwin's principle of natural selection. The idea is that in any population of self-reproducing organisms, there will be variations in the genetic material and upbringing that different individuals have. These differences will mean that some individuals are better able than others to draw the right conclusions about the world around them and to act accordingly. These individuals will be more likely to survive and reproduce and so their pattern of behavior and thought will come to dominate. It has certainly been true in the past that what we call intelligence and scientific discovery have conveyed a survival advantage. It is not so clear that this is still the case: our scientific discoveries may well destroy us all, and even if they don't, a complete unified theory may not make much difference to our chances of survival. However, provided the universe has evolved in a regular way, we might expect that the reasoning abilities that natural selection has given us would be valid also in our search for a complete unified theory, and so would not lead us to the wrong conclusions.

Because the partial theories that we already have are sufficient to make accurate predictions in all but the most extreme situations, the search for the ultimate theory of the universe seems difficult to justify on practical grounds. It is worth noting, though, that similar arguments could have been used against both relativity and quantum mechanics, and these theories have given us both nuclear energy and the microelectronics revolution! The discovery of a complete unified theory, therefore, may not aid the survival of our species. It may not even affect our life-style. But ever since the dawn of civilization, people

have not been content to see events as unconnected and inexplicable. They have craved an understanding of the underlying order in the world. Today we still yearn to know why we are here and where we came from. Humanity's deepest desire for knowledge is justification enough for our continuing quest. And our goal is nothing less than a complete description of the universe we live in.

CHAPTER 2

SPACE AND TIME

Our present ideas about the motion of bodies date back to Galileo and Newton. Before them people believed Aristotle, who said that the natural state of a body was to be at rest and that it moved only if driven by a force or impulse. It followed that a heavy body should fall faster than a light one, because it would have a greater pull toward the earth.

The Aristotelian tradition also held that one could work out all the laws that govern the universe by pure thought: it was not necessary to check by observation. So no one until Galileo bothered to see whether bodies of different weight did in fact fall at different speeds. It is said that Galileo demonstrated that Aristotle's belief was false by dropping weights from the leaning tower of Pisa. The story is almost certainly untrue, but Galileo did do something equivalent: he rolled balls of different weights down a smooth slope. The situation is similar to that of heavy bodies falling vertically, but it is easier to observe because the speeds are smaller. Galileo's measurements indicated that each body increased its speed at the same rate, no matter what its weight. For

example, if you let go of a ball on a slope that drops by one meter for every ten meters you go along, the ball will be traveling down the slope at a speed of about one meter per second after one second, two meters per second after two seconds, and so on, however heavy the ball. Of course a lead weight would fall faster than a feather, but that is only because a feather is slowed down by air resistance. If one drops two bodies that don't have much air resistance, such as two different lead weights, they fall at the same rate. On the moon, where there is no air to slow things down, the astronaut David R. Scott performed the feather and lead weight experiment and found that indeed they did hit the ground at the same time.

Galileo's measurements were used by Newton as the basis of his laws of motion. In Galileo's experiments, as a body rolled down the slope it was always acted on by the same force (its weight), and the effect was to make it constantly speed up. This showed that the real effect of a force is always to change the speed of a body, rather than just to set it moving, as was previously thought. It also meant that whenever a body is not acted on by any force, it will keep on moving in a straight line at the same speed. This idea was first stated explicitly in Newton's *Principia Mathematica*, published in 1687, and is known as Newton's first law. What happens to a body when a force does act on it is given by Newton's second law. This states that the body will accelerate, or change its speed, at a rate that is proportional to the force. (For example, the acceleration is twice as great if the force is twice as great.) The acceleration is also smaller the greater the mass (or quantity of matter) of the body. (The same force acting on a body of twice the mass will produce half the acceleration.) A familiar example is provided by a car: the more powerful the engine, the greater the acceleration, but the heavier the car, the smaller the acceleration for the same engine. In addition to his laws of motion, Newton discovered a law to describe the force of gravity, which states that every body attracts every other body with a force that is proportional to the mass of each body. Thus the force between two bodies would be twice as strong if one of the bodies

that body *A* had its mass doubled. This is what you might expect because one could think of the new body *A* as being made of two bodies with the original mass. Each would attract body *B* with the original force. Thus the total force between *A* and *B* would be twice the original force. And if, say, one of the bodies had twice the mass, and the other had three times the mass, then the force would be six times as strong. One can now see why all bodies fall at the same rate: a body of twice the weight will have twice the force of gravity pulling it down, but it will also have twice the mass. According to Newton's second law, these two effects will exactly cancel each other, so the acceleration will be the same in all cases.

Newton's law of gravity also tells us that the farther apart the bodies, the smaller the force. Newton's law of gravity says that the gravitational attraction of a star is exactly one quarter that of a similar star at half the distance. This law predicts the orbits of the earth, the moon, and the planets with great accuracy. If the law were that the gravitational attraction of a star went down faster or increased more rapidly with distance, the orbits of the planets would not be elliptical, they would either spiral in to the sun or escape from the sun.

The big difference between the ideas of Aristotle and those of Galileo and Newton is that Aristotle believed in a preferred state of rest, which any body would take up if it were not driven by some force or impulse. In particular, he thought that the earth was at rest. But it follows from Newton's laws that there is no unique standard of rest. One could equally well say that body *A* was at rest and body *B* was moving at constant speed with respect to body *A*, or that body *B* was at rest and body *A* was moving. For example, if one sets aside for a moment the rotation of the earth and its orbit round the sun, one could say that the earth was at rest and that a train on it was traveling north at ninety miles per hour or that the train was at rest and the earth was moving south at ninety miles per hour. If one carried out experiments with moving bodies on the train, all Newton's laws would still hold. For instance, playing Ping-Pong on the train, one would find that the

had obeyed Newton's laws, just like a ball on a table by the track. So there is no way to tell whether it is the train or the earth that is moving.

The lack of an absolute standard of rest meant that one could not determine whether two events that took place at different times occurred in the same position in space. For example, suppose our Ping-Pong ball on the train bounces straight up and down, hitting the table twice on the same spot one second apart. To someone on the track, the two bounces would seem to take place about forty meters apart, because the train would have traveled that far down the track between the bounces. The nonexistence of absolute rest therefore meant that one could not give an event an absolute position in space, as Aristotle had believed. The positions of events and the distances between them would be different for a person on the train and one on the track, and there would be no reason to prefer one person's position to the other's.

Newton was very worried by this lack of absolute position, or absolute space, as it was called, because it did not accord with his idea of an absolute God. In fact, he refused to accept lack of absolute space, even though it was implied by his laws. He was severely criticized for this irrational belief by many people, most notably by Bishop Berkeley, a philosopher who believed that all material objects and space and time are an illusion. When the famous Dr. Johnson was told of Berkeley's opinion, he cried, "I refute it thus!" and stubbed his toe on a large stone.

Both Aristotle and Newton believed in absolute time. That is, they believed that one could unambiguously measure the interval of time between two events, and that this time would be the same whoever measured it, provided they used a good clock. Time was completely separate from and independent of space. This is what most people would take to be the commonsense view. However, we have had to change our ideas about space and time. Although our apparently commonsense notions work well when dealing with things like apples, or planets that travel comparatively slowly, they don't work at all for things moving at or near the speed of light.

The fact that light travels at a finite, but very high, speed was first discovered in 1676 by the Danish astronomer Ole Christensen Roemer. He observed that the times at which the moons of Jupiter appeared to pass behind Jupiter were not evenly spaced, as one would expect if the moons went round Jupiter at a constant rate. As the earth and Jupiter orbit around the sun, the distance between them varies. Roemer noticed that eclipses of Jupiter's moons appeared later the farther we were from Jupiter. He argued that this was because the light from the moons took longer to reach us when we were farther away. His measurements of the variations in the distance of the earth from Jupiter were, however, not very accurate, and so his value for the speed of light was 140,000 miles per second, compared to the modern value of 186,000 miles per second. Nevertheless, Roemer's achievement, in not only proving that light travels at a finite speed, but also in measuring that speed, was remarkable—coming as it did eleven years before Newton's publication of *Principia Mathematica*.

A proper theory of the propagation of light didn't come until 1865, when the British physicist James Clerk Maxwell succeeded in unifying the partial theories that up to then had been used to describe the forces of electricity and magnetism. Maxwell's equations predicted that there could be wavelike disturbances in the combined electromagnetic field, and that these would travel at a fixed speed, like ripples on a pond. If the wavelength of these waves (the distance between one wave crest and the next) is a meter or more, they are what we now call radio waves. Shorter wavelengths are known as microwaves (a few centimeters) or infrared (more than a ten-thousandth of a centimeter). Visible light has a wavelength of between only forty and eighty millionths of a centimeter. Even shorter wavelengths are known as ultraviolet, X rays, and gamma rays.

Maxwell's theory predicted that radio or light waves should travel at a certain fixed speed. But Newton's theory had got rid of the idea of absolute rest, so if light was supposed to travel at a fixed speed, one would have to say what that fixed speed was to be measured relative to.

It was therefore suggested that there was a substance called the "ether" that was present everywhere, even in "empty" space. Light waves should travel through the ether as sound waves travel through air, and their speed should therefore be relative to the ether. Different observers, moving relative to the ether, would see light coming toward them at different speeds, but light's speed relative to the ether would remain fixed. In particular, as the earth was moving through the ether on its orbit round the sun, the speed of light measured in the direction of the earth's motion through the ether (when we were moving toward the source of the light) should be higher than the speed of light at right angles to that motion (when we are not moving toward the source). In 1887 Albert Michelson (who later became the first American to receive the Nobel Prize for physics) and Edward Morley carried out a very careful experiment at the Case School of Applied Science in Cleveland. They compared the speed of light in the direction of the earth's motion with that at right angles to the earth's motion. To their great surprise, they found they were exactly the same!

Between 1887 and 1905 there were several attempts, most notably by the Dutch physicist Hendrik Lorentz, to explain the result of the Michelson-Morley experiment in terms of objects contracting and clocks slowing down when they moved through the ether. However, in a famous paper in 1905, a hitherto unknown clerk in the Swiss patent office, Albert Einstein, pointed out that the whole idea of an ether was unnecessary, providing one was willing to abandon the idea of absolute time. A similar point was made a few weeks later by a leading French mathematician, Henri Poincaré. Einstein's arguments were closer to physics than those of Poincaré, who regarded this problem as mathematical. Einstein is usually given the credit for the new theory, but Poincaré is remembered by having his name attached to an important part of it.

The fundamental postulate of the theory of relativity, as it was called, was that the laws of science should be the same for all freely moving observers, no matter what their speed. This was true for Newton's laws of motion, but now the idea was extended to include

Maxwell's theory and the speed of light: all observers should measure the same speed of light, no matter how fast they are moving. This simple idea has some remarkable consequences. Perhaps the best known are the equivalence of mass and energy, summed up in Einstein's famous equation $E = mc^2$ (where E is energy, m is mass, and c is the speed of light), and the law that nothing may travel faster than the speed of light. Because of the equivalence of energy and mass, the energy which an object has due to its motion will add to its mass. In other words, it will make it harder to increase its speed. This effect is only really significant for objects moving at speeds close to the speed of light. For example, at 10 percent of the speed of light an object's mass is only 0.5 percent more than normal, while at 90 percent of the speed of light it would be more than twice its normal mass. As an object approaches the speed of light, its mass rises ever more quickly, so it takes more and more energy to speed it up further. It can in fact never reach the speed of light, because by then its mass would have become infinite, and by the equivalence of mass and energy, it would have taken an infinite amount of energy to get it there. For this reason, any normal object is forever confined by relativity to move at speeds slower than the speed of light. Only light, or other waves that have no intrinsic mass, can move at the speed of light.

An equally remarkable consequence of relativity is the way it has revolutionized our ideas of space and time. In Newton's theory, if a pulse of light is sent from one place to another, different observers would agree on the time that the journey took (since time is absolute), but will not always agree on how far the light traveled (since space is not absolute). Since the speed of the light is just the distance it has traveled divided by the time it has taken, different observers would measure different speeds for the light. In relativity, on the other hand, all observers *must* agree on how fast light travels. They still, however, do not agree on the distance the light has traveled, so they must therefore now also disagree over the time it has taken. (The time taken is the distance the light has traveled—which the observers do not agree

on—divided by the light's speed—which they do agree on). In other words, the theory of relativity put an end to the idea of absolute time! It appeared that each observer must have his own measure of time, as recorded by a clock carried with him, and that identical clocks carried by different observers would not necessarily agree.

Each observer could use radar to say where and when an event took place by sending out a pulse of light or radio waves. Part of the pulse is reflected back at the event and the observer measures the time at which he receives the echo. The time of the event is then said to be the time halfway between when the pulse was sent and the time when the reflection was received back: the distance of the event is half the time taken for this round trip, multiplied by the speed of light. (An event, in this sense, is something that takes place at a single point in space, at a specified point in time.) This idea is shown in Fig. 2.1, which is an example of a space-time diagram. Using this procedure, observers who are moving relative to each other will assign different times and positions to the same event. No particular observer's measurements are any more correct than any other observer's, but all the measurements are related. Any observer can work out precisely what time and position any other observer will assign to an event, provided he knows the other observer's relative velocity.

Nowadays we use just this method to measure distances precisely, because we can measure time more accurately than length. In effect, the meter is defined to be the distance traveled by light in 0.000000003335640952 second, as measured by a cesium clock. (The reason for that particular number is that it corresponds to the historical definition of the meter—in terms of two marks on a particular platinum bar kept in Paris.) Equally, we can use a more convenient, new unit of length called a light-second. This is simply defined as the distance that light travels in one second. In the theory of relativity, we now define distance in terms of time and the speed of light, so it follows automatically that every observer will measure light to have the same speed (by definition, 1 meter per 0.000000003335640952 second).

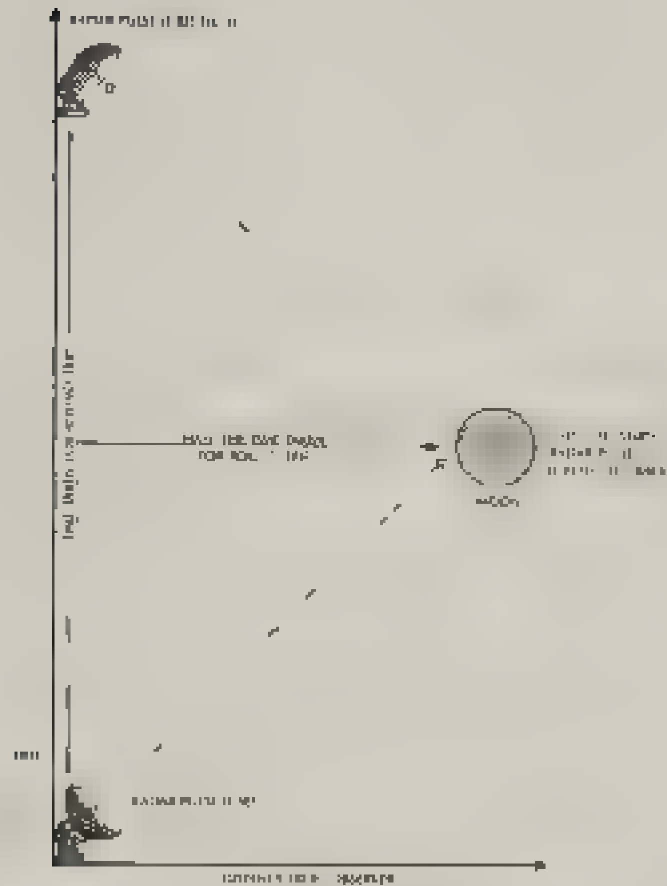

FIGURE 2.1 Time is measured vertically, and the distance from the observer is measured horizontally. The observer's path through space and time is shown as the vertical line on the left. The paths of light rays to and from the event are the diagonal lines.

There is no need to introduce the idea of an ether, whose presence anyway cannot be detected, as the Michelson-Morley experiment showed. The theory of relativity does, however, force us to change fundamentally our ideas of space and time. We must accept that time is not completely separate from and independent of space, but is combined with it to form an object called space-time.

It is a matter of common experience that one can describe the position of a point in space by three numbers, or coordinates. For instance, one can say that a point in a room is seven feet from one wall, three feet from another, and five feet above the floor. Or one could specify that a point was at a certain latitude and longitude and a certain height above sea level. One is free to use any three suitable coordinates

although they have only a limited range of validity. One would not specify the position of the moon in terms of miles north and miles west of Piccadilly Circus and feet above sea level. Instead, one might describe it in terms of distance from the sun, distance from the plane of the orbits of the planets, and the angle between the line joining the moon to the sun and the line joining the sun to a nearby star such as Alpha Centauri. Even these coordinates would not be of much use in describing the position of the sun in our galaxy or the position of our galaxy in the local group of galaxies. In fact, one may describe the whole universe in terms of a collection of overlapping patches. In each patch, one can use a different set of three coordinates to specify the position of a point.

An event is something that happens at a particular point in space and at a particular time. So one can specify it by four numbers or coordinates. Again, the choice of coordinates is arbitrary; one can use any three well-defined spatial coordinates and any measure of time. In relativity, there is no real distinction between the space and time coordinates, just as there is no real difference between any two space coordinates. One could choose a new set of coordinates in which, say, the first space coordinate was a combination of the old first and second space coordinates. For instance, instead of measuring the position of a point on the earth in miles north of Piccadilly and miles west of Piccadilly, one could use miles north-east of Piccadilly, and miles north-west of Piccadilly. Similarly, in relativity, one could use a new time coordinate that was the old time (in seconds) plus the distance (in light-seconds) north of Piccadilly.

It is often helpful to think of the four coordinates of an event as specifying its position in a four-dimensional space called space-time. It is impossible to imagine a four-dimensional space. I personally find it hard enough to visualize three-dimensional space! However, it is easy to draw diagrams of two-dimensional spaces, such as the surface of the earth. (The surface of the earth is two-dimensional because the position of a point can be specified by two coordinates, latitude and longitude.)

so we generally use diagrams in which time increases upward and one of the spatial dimensions is shown horizontally. The other two spatial dimensions are ignored or, sometimes, one of them is indicated by perspective. (These are called space-time diagrams, like Fig. 2.1.) For example, in Fig. 2.2 time is measured upward in years and the distance along the line from the sun to Alpha Centauri is measured horizontally in miles. The paths of the sun and of Alpha Centauri through space-time are shown as the vertical lines on the left and right of the diagram. A ray of light from the sun follows the diagonal line, and takes four years to get from the sun to Alpha Centauri.

As we have seen, Maxwell's equations predicted that the speed of light should be the same whatever the speed of the source, and this has been confirmed by accurate measurements. It follows from this that if a pulse of light is emitted at a particular time at a particular point in

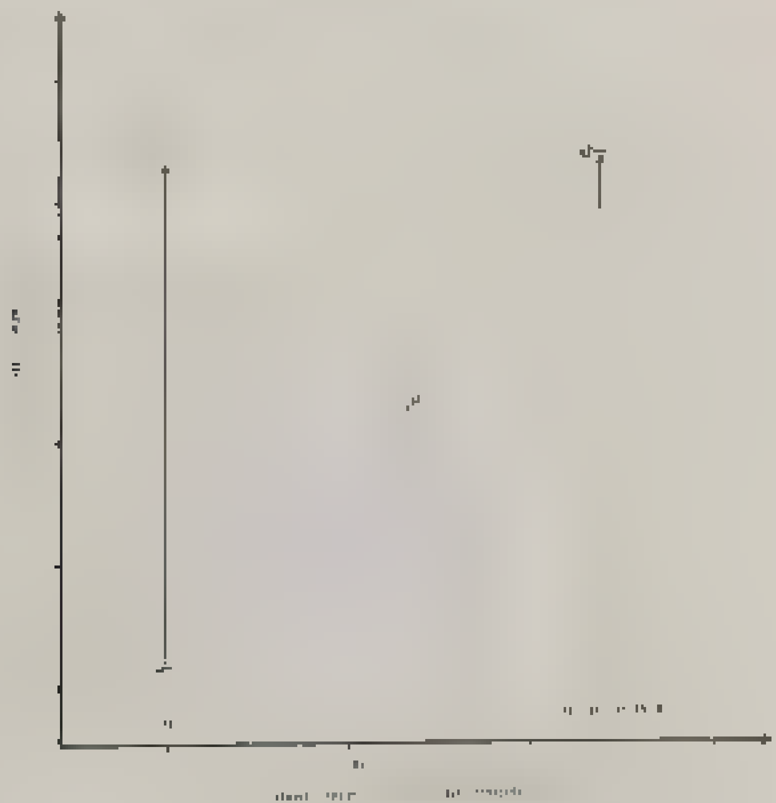

FIGURE 2.2

space, then as time goes on it will spread out as a sphere of light whose size and position are independent of the speed of the source. After one millionth of a second the light will have spread out to form a sphere with a radius of 300 meters; after two millionths of a second, the radius will be 600 meters; and so on. It will be like the ripples that spread out on the surface of a pond when a stone is thrown in. The ripples spread out as a circle that gets bigger as time goes on. If one stacks snapshots of the ripples at different times one above the other, the expanding circle of ripples will mark out a cone whose tip is at the place and time at which the stone hit the water (Fig. 2.3). Similarly, the light spreading out from an event forms a (three-dimensional) cone in the (four-dimensional) space-time. This cone is called the future light cone of the event. In the same way we can draw another cone, called the past light cone, which is the set of events from which a pulse of light is able to reach the given event (Fig. 2.4).

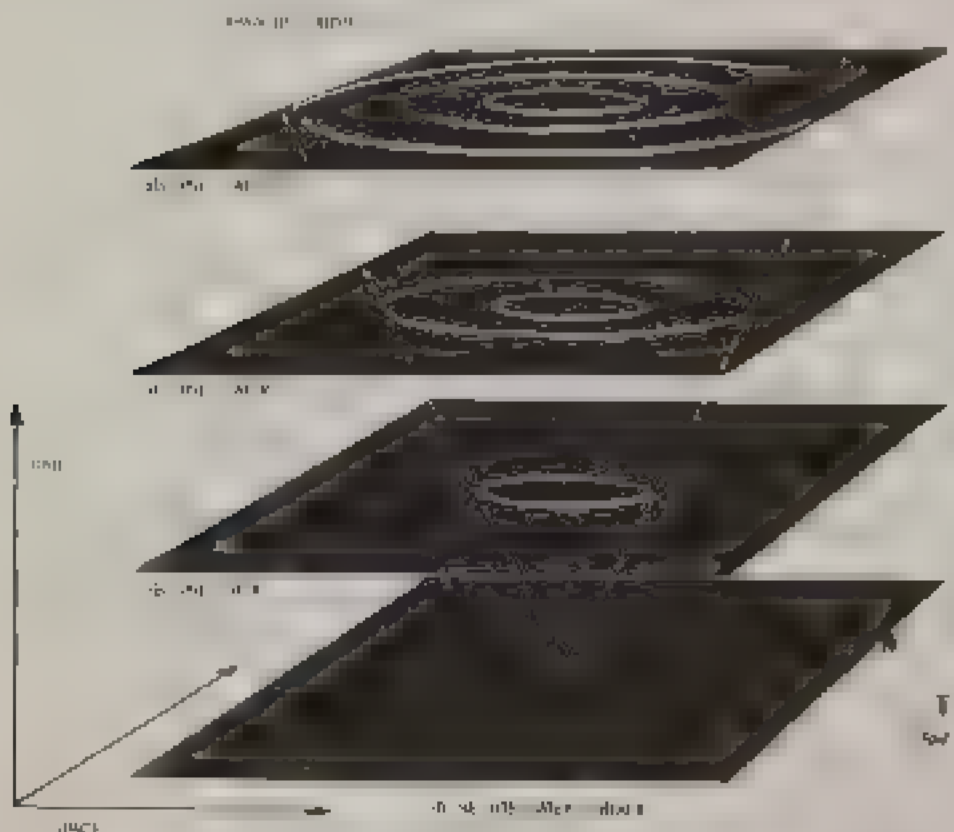

FIGURE 2.3

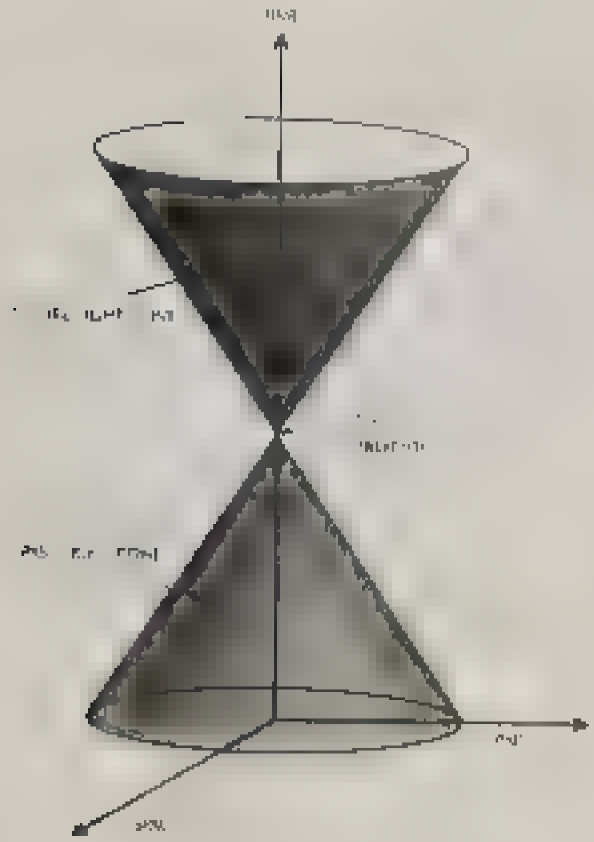

FIGURE 2.4

Given an event P, one can divide the other events in the universe into three classes. Those events that can be reached from the event P by a particle or wave traveling at or below the speed of light are said to be in the future of P. They will lie within or on the expanding sphere of light emitted from the event P. Thus they will lie within or on the future light cone of P in the space-time diagram. Only events in the future of P can be affected by what happens at P because nothing can travel faster than light.

Similarly, the past of P can be defined as the set of all events from which it is possible to reach the event P traveling at or below the speed of light. It is thus the set of events that can affect what happens at P. The events that do not lie in the future or past of P are said to lie in the elsewhere of P (Fig. 2.5). What happens at such events can neither affect nor be affected by what happens at P. For example, if the sun

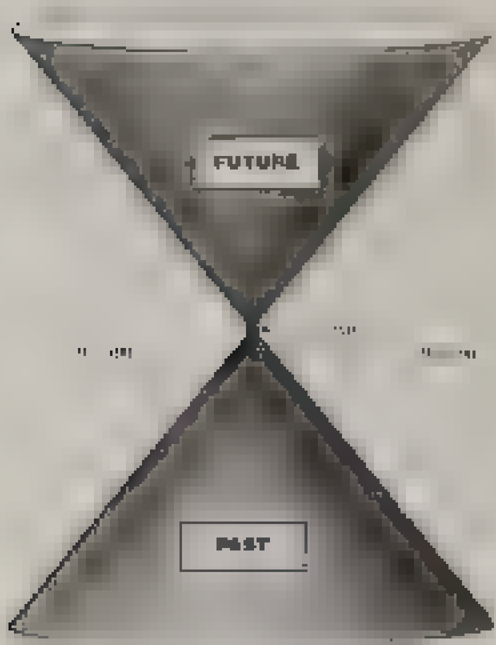

FIGURE 2.5

were to cease to shine, it would not affect things on earth at the present time because they would be in the elsewhere of the event when the sun went out (Fig. 2.6). We would know about it only after eight minutes, the time it takes light to reach us from the sun. Only then would events on earth lie in the future light cone of the event at which the sun went out. Similarly, we do not know what is happening at the moment farther away in the universe: the light that we see from distant galaxies left them millions of years ago, and in the case of the most distant object that we have seen, the light left some eight thousand million years ago. Thus, when we look at the universe, we are seeing it as it was in the past.

If one neglects gravitational effects, as Einstein and Poincaré did in 1905, one has what is called the special theory of relativity. For every event in space-time we may construct a light cone (the set of all possible paths of light in space-time emitted at that event), and since the speed of light is the same at every event and in every direction, all the light cones will be identical and will all point in the same direction. The

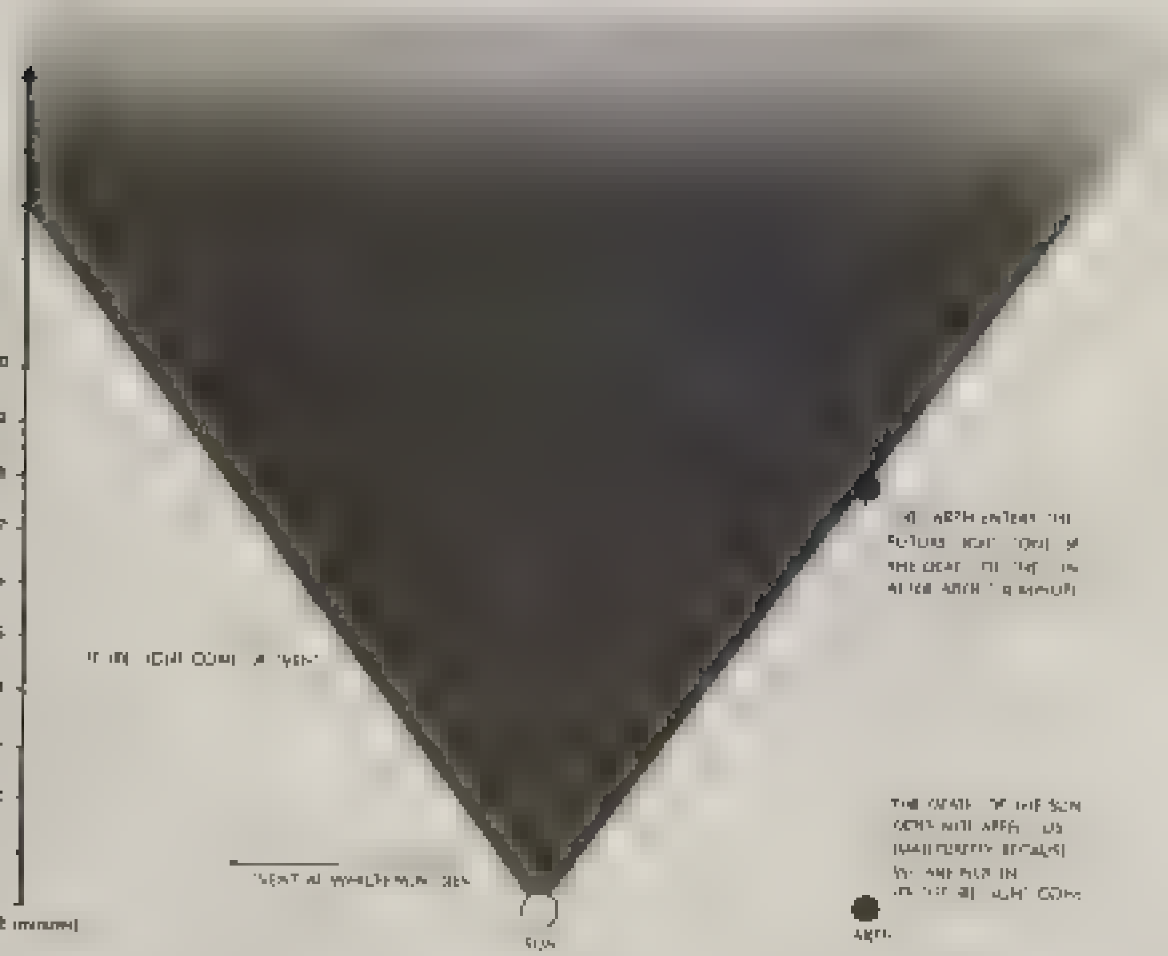

FIGURE 2.6

theory also implies that nothing can travel faster than light. This means that the path of any object through space and time must be represented by a line that lies within the light cone at each event on it (Fig. 2.7). The special theory of relativity was very successful in explaining that the speed of light appears the same to all observers (as shown by the Michelson-Morley experiment) and in describing what happens when things move at speeds close to the speed of light. However, it was inconsistent with the Newtonian theory of gravity, which said that objects attracted each other with a force that depended on the distance between them. This meant that if one moved one of the objects, the force on the other one would change instantaneously. Or in other words, gravitational effects should travel with infinite velocity,

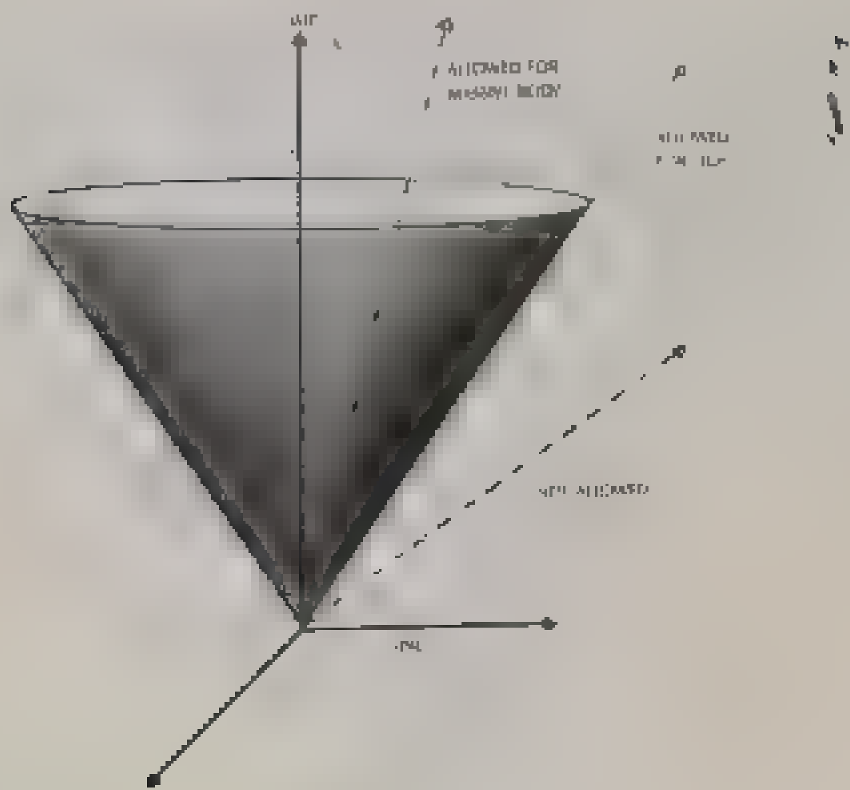

FIGURE 2.7

instead of at or below the speed of light, as the special theory of relativity required. Einstein made a number of unsuccessful attempts between 1908 and 1914 to find a theory of gravity that was consistent with special relativity. Finally, in 1915, he proposed what we now call the general theory of relativity.

Einstein made the revolutionary suggestion that gravity is not a force like other forces, but is a consequence of the fact that space-time is not flat, as had been previously assumed: it is curved, or "warped," by the distribution of mass and energy in it. Bodies like the earth are not made to move on curved orbits by a force called gravity; instead, they follow the nearest thing to a straight path in a curved space, which is called a geodesic. A geodesic is the shortest (or longest) path between two nearby points. For example, the surface of the earth is a two-dimensional curved space. A geodesic on the earth is called a great circle, and is the shortest route between two points (Fig. 2.8). As the

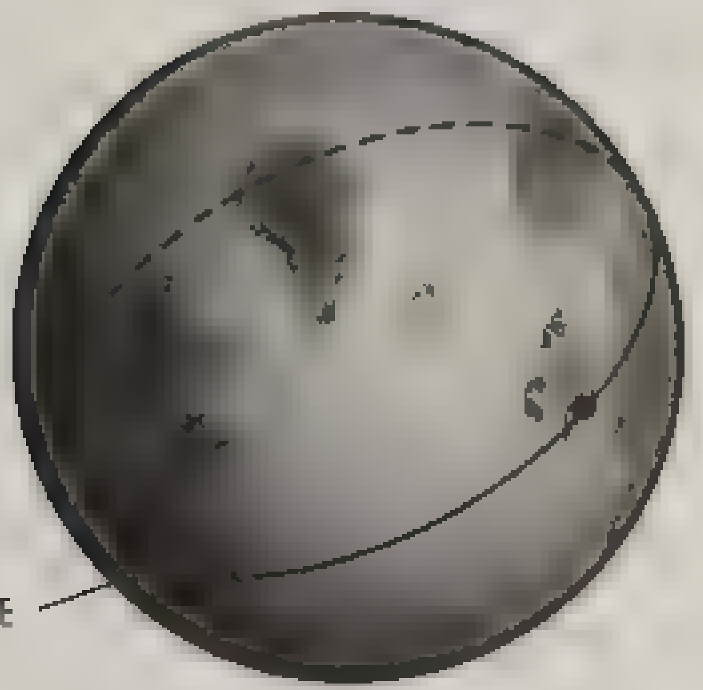

FIGURE 2.8

geodesic is the shortest path between any two airports, this is the route an airline navigator will tell the pilot to fly along. In general relativity, bodies always follow straight lines in four-dimensional space-time, but they nevertheless appear to us to move along curved paths in our three-dimensional space. (This is rather like watching an airplane flying over hilly ground. Although it follows a straight line in three-dimensional space, its shadow follows a curved path on the two-dimensional ground.)

The mass of the sun curves space-time in such a way that although the earth follows a straight path in four-dimensional space-time, it appears to us to move along a circular orbit in three-dimensional space. In fact, the orbits of the planets predicted by general relativity are almost exactly the same as those predicted by the Newtonian theory of gravity. However, in the case of Mercury, which, being the nearest planet to the sun, feels the strongest gravitational effects, and has a rather elongated orbit, general relativity predicts that the long axis of the ellipse should rotate about the sun at a rate of about one degree in

ten thousand years. Small though this effect is, it had been noticed before 1915 and served as one of the first confirmations of Einstein's theory. In recent years the even smaller deviations of the orbits of the other planets from the Newtonian predictions have been measured by radar and found to agree with the predictions of general relativity.

Light rays too must follow geodesics in space-time. Again, the fact that space is curved means that light no longer appears to travel in straight lines in space. So general relativity predicts that light should be bent by gravitational fields. For example, the theory predicts that the light cones of points near the sun would be slightly bent inward, on account of the mass of the sun. This means that light from a distant star that happened to pass near the sun would be deflected through a small angle, causing the star to appear in a different position to an observer on the earth (Fig. 2.9). Of course, if the light from the star always

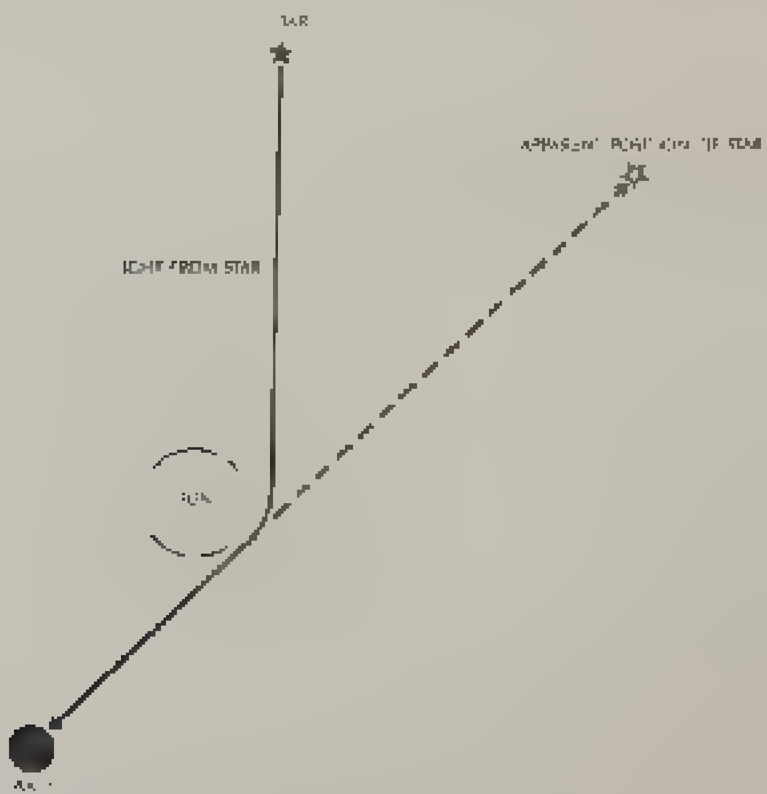

FIGURE 2.9

firmed by a number of later observations.

ence in the speed of clocks at different heights above the earth is now of considerable practical importance, with the advent of very accurate navigation systems based on signals from satellites. If one ignored the predictions of general relativity, the position that one calculated would be wrong by several miles!

Newton's laws of motion put an end to the idea of absolute position in space. The theory of relativity gets rid of absolute time. Consider a pair of twins. Suppose that one twin goes to live on the top of a mountain while the other stays at sea level. The first twin would age faster than the second. Thus, if they met again, one would be older than the other. In this case, the difference in ages would be very small, but it would be much larger if one of the twins went for a long trip in a spaceship at nearly the speed of light. When he returned, he would be much younger than the one who stayed on earth. This is known as the twins paradox, but it is a paradox only if one has the idea of absolute time at the back of one's mind. In the theory of relativity there is no unique absolute time, but instead each individual has his own personal measure of time that depends on where he is and how he is moving.

Before 1915, space and time were thought of as a fixed arena in which events took place, but which was not affected by what happened in it. This was true even of the special theory of relativity. Bodies moved, forces attracted and repelled, but time and space simply continued, unaffected. It was natural to think that space and time went on forever.

The situation, however, is quite different in the general theory of relativity. Space and time are now dynamic quantities: when a body moves, or a force acts, it affects the curvature of space and time—and in turn the structure of space-time affects the way in which bodies move and forces act. Space and time not only affect but also are affected by everything that happens in the universe. Just as one cannot talk about events in the universe without the notions of space and time, so in general relativity it became meaningless to talk about space and time outside the limits of the universe.

In the following decades this new understanding of space and time was to revolutionize our view of the universe. The old idea of an essentially unchanging universe that could have existed, and could continue to exist, forever was replaced by the notion of a dynamic, expanding universe that seemed to have begun a finite time ago, and that might end at a finite time in the future. That revolution forms the subject of the next chapter. And years later, it was also to be the starting point for my work in theoretical physics. Roger Penrose and I showed that Einstein's general theory of relativity implied that the universe must have a beginning and, possibly, an end.

CHAPTER 3

THE EXPANDING UNIVERSE

If one looks at the sky on a clear, moonless night, the brightest objects one sees are likely to be the planets Venus, Mars, Jupiter, and Saturn. There will also be a very large number of stars, which are just like our own sun but much farther from us. Some of these fixed stars do, in fact, appear to change very slightly their positions relative to each other as the earth orbits around the sun: they are not really fixed at all! This is because they are comparatively near to us. As the earth goes round the sun, we see them from different positions against the background of more distant stars. This is fortunate, because it enables us to measure directly the distance of these stars from us: the nearer they are, the more they appear to move. The nearest star, called Proxima Centauri, is found to be about four light-years away (the light from it takes about four years to reach earth), or about twenty-three million million miles. Most of the other stars that are visible to the naked eye lie within a few hundred light-years of us. Our sun, for comparison, is a mere eight light-minutes away! The visible stars appear spread all over the night sky, but are particularly concentrated in one band

which we call the Milky Way. As long ago as 1750 some astronomers were suggesting that the appearance of the Milky Way could be explained if most of the visible stars lie in a single disklike configuration, one example of what we now call a spiral galaxy. Only a few decades later, the astronomer Sir William Herschel confirmed this idea by painstakingly cataloging the positions and distances of vast numbers of stars. Even so, the idea gained complete acceptance only early this century.

Our modern picture of the universe dates back to only 1924, when the American astronomer Edwin Hubble demonstrated that ours was not the only galaxy. There were in fact many others, with vast tracts of empty space between them. In order to prove this, he needed to determine the distances to these other galaxies, which are so far away that, unlike nearby stars, they really do appear fixed. Hubble was forced, therefore, to use indirect methods to measure the distances. Now, the apparent brightness of a star depends on two factors: how much light it radiates (its luminosity), and how far it is from us. For nearby stars, we can measure their apparent brightness and their distance, and so we can work out their luminosity. Conversely, if we knew the luminosity of stars in other galaxies, we could work out their distance by measuring their apparent brightness. Hubble noted that certain types of stars always have the same luminosity when they are near enough for us to measure; therefore, he argued, if we found such stars in another galaxy, we could assume that they had the same luminosity—and so calculate the distance to that galaxy. If we could do this for a number of stars in the same galaxy, and our calculations always gave the same distance, we could be fairly confident of our estimate.

In this way, Edwin Hubble worked out the distances to nine different galaxies. We now know that our galaxy is only one of some hundred thousand million that can be seen using modern telescopes, each galaxy itself containing some hundred thousand million stars. Fig. 3.1 shows a picture of one spiral galaxy that is similar to what we

FIGURE 3.1

think ours must look like to someone living in another galaxy. We live in a galaxy that is about one hundred thousand light-years across and is slowly rotating; the stars in its spiral arms orbit around its center about once every several hundred million years. Our sun is just an ordinary, average-sized, yellow star, near the inner edge of one of the spiral arms. We have certainly come a long way since Aristotle and Ptolemy, when we thought that the earth was the center of the universe!

Stars are so far away that they appear to us to be just pinpoints of light. We cannot see their size or shape. So how can we tell different types of stars apart? For the vast majority of stars, there is only one characteristic feature that we can observe—the color of their light. Newton discovered that if light from the sun passes through a triangular-shaped piece of glass, called a prism, it breaks up into its component colors (its spectrum) as in a rainbow. By focusing a telescope on an individual star or galaxy, one can similarly observe the

[illegible] star's atmosphere.

[illegible]

growing all the time.

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[illegible] what Hubble found.

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the uniform expansion of the universe

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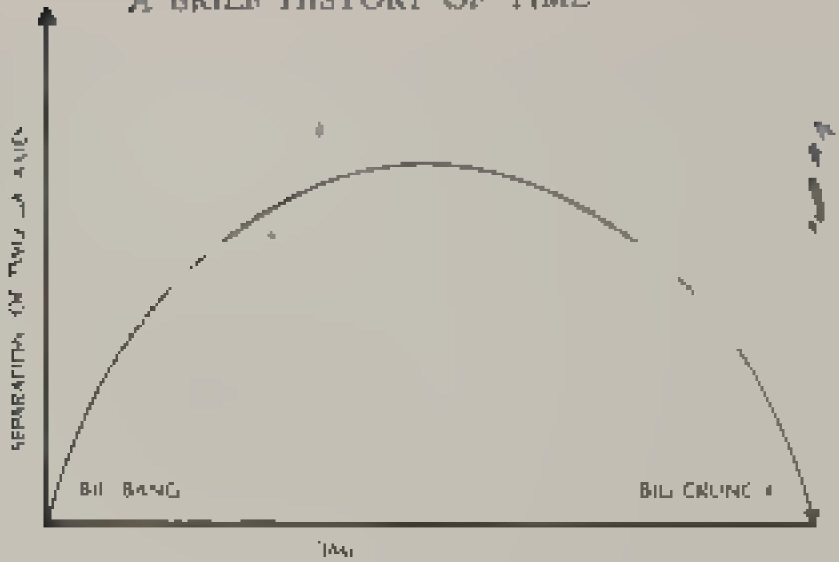

FIGURE 3.2

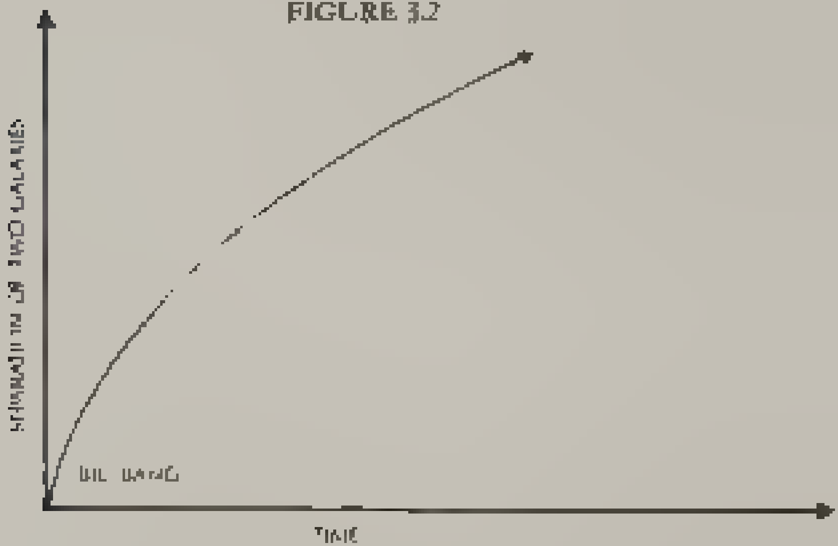

FIGURE 3.3

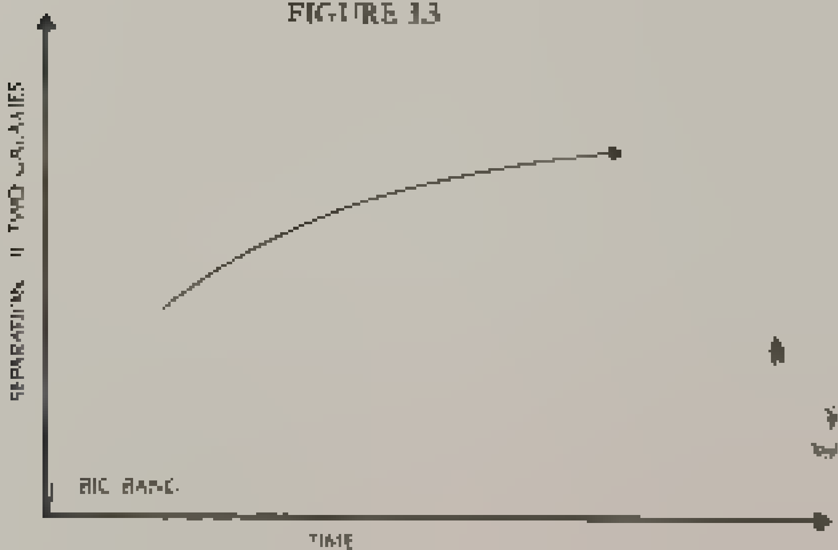

FIGURE 3.4

at a steady speed. Finally, there is a third kind of solution, in which the universe is expanding only just fast enough to avoid recollapse. In this case the separation, shown in Fig. 3.4, also starts at zero and increases forever. However, the speed at which the galaxies are moving apart gets smaller and smaller, although it never quite reaches zero.

A remarkable feature of the first kind of Friedmann model is that in it the universe is not infinite in space, but neither does space have any boundary. Gravity is so strong that space is bent round onto itself, making it rather like the surface of the earth. If one keeps traveling in a certain direction on the surface of the earth, one never comes up against an impassable barrier or falls over the edge, but eventually comes back to where one started. In the first Friedmann model, space is just like this, but with three dimensions instead of two for the earth's surface. The fourth dimension, time, is also finite in extent, but it is like a line with two ends or boundaries, a beginning and an end. We shall see later that when one combines general relativity with the uncertainty principle of quantum mechanics, it is possible for both space and time to be finite without any edges or boundaries.

The idea that one could go right round the universe and end up where one started makes good science fiction, but it doesn't have much practical significance, because it can be shown that the universe would recollapse to zero size before one could get round. You would need to travel faster than light in order to end up where you started before the universe came to an end—and that is not allowed!

In the first kind of Friedmann model, which expands and recollapses, space is bent in on itself, like the surface of the earth. It is therefore finite in extent. In the second kind of model, which expands forever, space is bent the other way, like the surface of a saddle. So in this case space is infinite. Finally, in the third kind of Friedmann model, with just the critical rate of expansion, space is flat (and therefore is also infinite).

But which Friedmann model describes our universe? Will the universe eventually stop expanding and start contracting, or will it expand forever? To answer this question we need to know the present

rate of expansion of the universe and its present average density. If the density is less than a certain critical value, determined by the rate of expansion, the gravitational attraction will be too weak to halt the expansion. If the density is greater than the critical value, gravity will stop the expansion at some time in the future and cause the universe to recollapse.

We can determine the present rate of expansion by measuring the velocities at which other galaxies are moving away from us, using the Doppler effect. This can be done very accurately. However, the distances to the galaxies are not very well known because we can only measure them indirectly. So all we know is that the universe is expanding by between 5 percent and 10 percent every thousand million years. However, our uncertainty about the present average density of the universe is even greater. If we add up the masses of all the stars that we can see in our galaxy and other galaxies, the total is less than one hundredth of the amount required to halt the expansion of the universe, even for the lowest estimate of the rate of expansion. Our galaxy and other galaxies, however, must contain a large amount of "dark matter" that we cannot see directly, but which we know must be there because of the influence of its gravitational attraction on the orbits of stars in the galaxies. Moreover, most galaxies are found in clusters, and we can similarly infer the presence of yet more dark matter in between the galaxies in these clusters by its effect on the motion of the galaxies. When we add up all this dark matter, we still get only about one tenth of the amount required to halt the expansion. However, we cannot exclude the possibility that there might be some other form of matter, distributed almost uniformly throughout the universe, that we have not yet detected and that might still raise the average density of the universe up to the critical value needed to halt the expansion. The present evidence therefore suggests that the universe will probably expand forever, but all we can really be sure of is that even if the universe is going to recollapse, it won't do so for at least another ten thousand million years, since it has already been expanding for at least

[illegible]

abandoned.

say whether the universe would have had a singularity, a big bang, if the general theory of relativity was correct. However, it did not resolve the crucial question: Does general relativity predict that our universe should have had a big bang, a beginning of time? The answer to this came out of a completely different approach introduced by a British mathematician and physicist, Roger Penrose, in 1965. Using the way light cones behave in general relativity, together with the fact that gravity is always attractive, he showed that a star collapsing under its own gravity is trapped in a region whose surface eventually shrinks to zero size. And, since the surface of the region shrinks to zero, so too must its volume. All the matter in the star will be compressed into a region of zero volume, so the density of matter and the curvature of space-time become infinite. In other words, one has a singularity contained within a region of space-time known as a black hole.

At first sight, Penrose's result applied only to stars; it didn't have anything to say about the question of whether the entire universe had a big bang singularity in its past. However, at the time that Penrose produced his theorem, I was a research student desperately looking for a problem with which to complete my Ph.D. thesis. Two years before, I had been diagnosed as suffering from ALS, commonly known as Lou Gehrig's disease, or motor neuron disease, and given to understand that I had only one or two more years to live. In these circumstances there had not seemed much point in working on my Ph.D. – I did not expect to survive that long. Yet two years had gone by and I was not that much worse. In fact, things were going rather well for me and I had gotten engaged to a very nice girl, Jane Wilde. But in order to get married, I needed a job, and in order to get a job, I needed a Ph.D.

In 1965 I read about Penrose's theorem that any body undergoing gravitational collapse must eventually form a singularity. I soon realized that if one reversed the direction of time in Penrose's theorem, so that the collapse became an expansion, the conditions of his theorem would still hold, provided the universe were roughly like a Friedmann model on large scales at the present time. Penrose's theorem had shown

that any collapsing star must end up in a singularity; the time-reverse argument showed that any Friedmann-like expanding universe must have begun with a singularity. For technical reasons, Penrose's theorem required that the universe be infinite in space. So I could in fact use it to prove that there should be a singularity only if the universe was expanding fast enough to avoid collapsing again (since only those Friedmann models were infinite in space).

During the next few years I developed new mathematical techniques to remove this and other technical conditions from the theorems that proved that singularities must occur. The final result was a joint paper by Penrose and myself in 1970, which at last proved that there must have been a big bang singularity provided only that general relativity is correct and the universe contains as much matter as we observe. There was a lot of opposition to our work, partly from the Russians because of their Marxist belief in scientific determinism, and partly from people who felt that the whole idea of singularities was repugnant and spoiled the beauty of Einstein's theory. However, one cannot really argue with a mathematical theorem. So in the end our work became generally accepted and nowadays nearly everyone assumes that the universe started with a big bang singularity. It is perhaps ironic that, having changed my mind, I am now trying to convince other physicists that there was in fact no singularity at the beginning of the universe—as we shall see later, it can disappear once quantum effects are taken into account.

We have seen in this chapter how, in less than half a century, man's view of the universe, formed over millennia, has been transformed. Hubble's discovery that the universe was expanding, and the realization of the insignificance of our own planet in the vastness of the universe, were just the starting point. As experimental and theoretical evidence mounted, it became more and more clear that the universe must have had a beginning in time, until in 1970 this was finally proved by Penrose and myself, on the basis of Einstein's general theory of relativity. That proof showed that general relativity is only

an incomplete theory: it cannot tell us how the universe started off, because it predicts that all physical theories, including itself, break down at the beginning of the universe. However, general relativity claims to be only a partial theory, so what the singularity theorems really show is that there must have been a time in the very early universe when the universe was so small that one could no longer ignore the small-scale effects of the other great partial theory of the twentieth century, quantum mechanics. At the start of the 1970s, then, we were forced to turn our search for an understanding of the universe from our theory of the extraordinarily vast to our theory of the extraordinarily tiny. That theory, quantum mechanics, will be described next, before we turn to the efforts to combine the two partial theories into a single quantum theory of gravity.

CHAPTER 4

THE UNCERTAINTY PRINCIPLE

The success of scientific theories, particularly Newton's theory of gravity, led the French scientist the Marquis de Laplace at the beginning of the nineteenth century to argue that the universe was completely deterministic. Laplace suggested that there should be a set of scientific laws that would allow us to predict everything that would happen in the universe, if only we knew the complete state of the universe at one time. For example, if we knew the positions and speeds of the sun and the planets at one time, then we could use Newton's laws to calculate the state of the Solar System at any other time. Determinism seems fairly obvious in this case, but Laplace went further to assume that there were similar laws governing everything else, including human behavior.

The doctrine of scientific determinism was strongly resisted by many people, who felt that it infringed God's freedom to intervene in the world, but it remained the standard assumption of science until the early years of this century. One of the first indications that this belief would have to be abandoned came when calculations by the British

scientists Lord Rayleigh and Sir James Jeans suggested that a hot object, or body, such as a star, must radiate energy at an infinite rate. According to the laws we believed at the time, a hot body ought to give off electromagnetic waves (such as radio waves, visible light, or X rays) equally at all frequencies. For example, a hot body should radiate the same amount of energy in waves with frequencies between one and two million million waves a second as in waves with frequencies between two and three million million waves a second. Now since the number of waves a second is unlimited, this would mean that the total energy radiated would be infinite.

In order to avoid this obviously ridiculous result, the German scientist Max Planck suggested in 1900 that light, X rays, and other waves could not be emitted at an arbitrary rate, but only in certain packets that he called quanta. Moreover, each quantum had a certain amount of energy that was greater the higher the frequency of the waves, so at a high enough frequency the emission of a single quantum would require more energy than was available. Thus the radiation at high frequencies would be reduced, and so the rate at which the body lost energy would be finite.

The quantum hypothesis explained the observed rate of emission of radiation from hot bodies very well, but its implications for determinism were not realized until 1926, when another German scientist, Werner Heisenberg, formulated his famous uncertainty principle. In order to predict the future position and velocity of a particle, one has to be able to measure its present position and velocity accurately. The obvious way to do this is to shine light on the particle. Some of the waves of light will be scattered by the particle and this will indicate its position. However, one will not be able to determine the position of the particle more accurately than the distance between the wave crests of light, so one needs to use light of a short wavelength in order to measure the position of the particle precisely. Now, by Planck's quantum hypothesis, one cannot use an arbitrarily small amount of light; one has to use at least one quantum. This quantum will disturb the

particle and change its speed in a way that cannot be predicted. Moreover, the more accurately one measures the position, the shorter the wavelength of the light that one needs and hence the higher the energy of a single quantum. So the velocity of the particle will be disturbed by a larger amount. In other words, the more accurately you try to measure the position of the particle, the less accurately you can measure its speed, and vice versa. Heisenberg showed that the uncertainty in the position of the particle times the uncertainty in its velocity times the mass of the particle can never be smaller than a certain quantity, which is known as Planck's constant. Moreover, this limit does not depend on the way in which one tries to measure the position or velocity of the particle, or on the type of particle: Heisenberg's uncertainty principle is a fundamental, inescapable property of the world.

The uncertainty principle had profound implications for the way in which we view the world. Even after more than seventy years they have not been fully appreciated by many philosophers, and are still the subject of much controversy. The uncertainty principle signaled an end to Laplace's dream of a theory of science, a model of the universe that would be completely deterministic: one certainly cannot predict future events exactly if one cannot even measure the present state of the universe precisely! We could still imagine that there is a set of laws that determine events completely for some supernatural being, who could observe the present state of the universe without disturbing it. However, such models of the universe are not of much interest to us ordinary mortals. It seems better to employ the principle of economy known as Occam's razor and cut out all the features of the theory that cannot be observed. This approach led Heisenberg, Erwin Schrödinger, and Paul Dirac in the 1920s to reformulate mechanics into a new theory called quantum mechanics, based on the uncertainty principle. In this theory particles no longer had separate, well-defined positions and velocities that could not be observed. Instead, they had a quantum state, which was a combination of position and velocity.

[illegible] large-scale structure of the universe.

[illegible]

it is only the observations of the world that may be described in those terms. There is thus a duality between waves and particles in quantum mechanics: for some purposes it is helpful to think of particles as waves and for other purposes it is better to think of waves as particles. An important consequence of this is that one can observe what is called interference between two sets of waves or particles. That is to say, the crests of one set of waves may coincide with the troughs of the other set. The two sets of waves then cancel each other out rather than adding up to a stronger wave as one might expect (Fig. 4.1). A familiar example of interference in the case of light is the colors that are often seen in soap bubbles. These are caused by reflection of light from the two sides of the thin film of water forming the bubble. White light consists of light waves of all different wavelengths, or colors. For certain wavelengths the crests of the waves reflected from one side of the soap film coincide with the troughs reflected from the other side. The colors corresponding to these wavelengths are absent from the reflected light, which therefore appears to be colored.

Interference can also occur for particles, because of the duality introduced by quantum mechanics. A famous example is the so-called two-slit experiment (Fig. 4.2). Consider a partition with two narrow parallel slits in it. On one side of the partition one places a source of light of a particular color (that is, of a particular wavelength). Most of the light will hit the partition, but a small amount will go through the

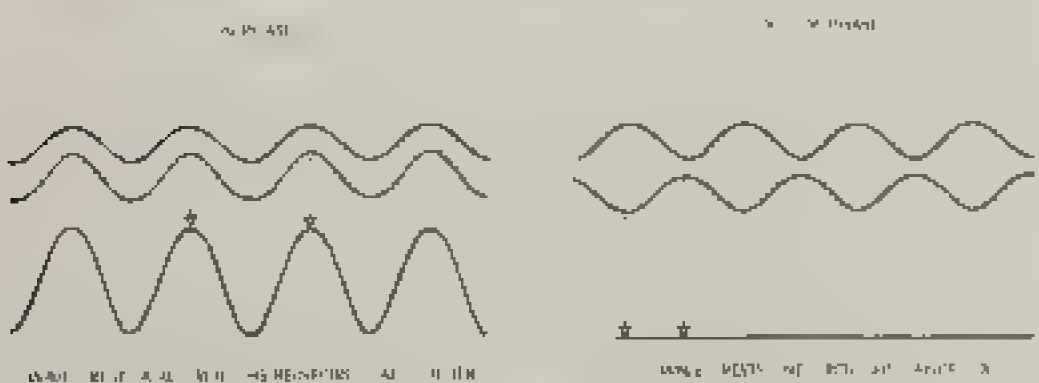

FIGURE 4.1

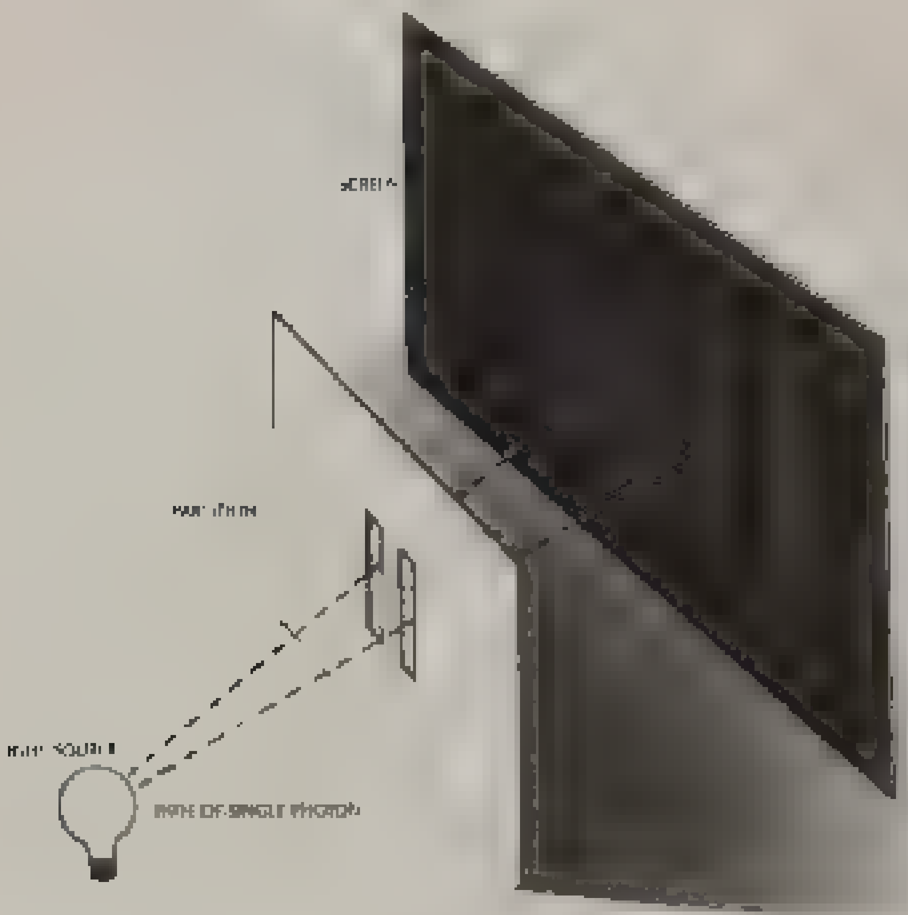

FIGURE 4.2

slits. Now suppose one places a screen on the far side of the partition from the light. Any point on the screen will receive waves from the two slits. However, in general, the distance the light has to travel from the source to the screen via the two slits will be different. This will mean that the waves from the slits will not be in phase with each other when they arrive at the screen: in some places the waves will cancel each other out, and in others they will reinforce each other. The result is a characteristic pattern of light and dark fringes.

The remarkable thing is that one gets exactly the same kind of fringes if one replaces the source of light by a source of particles such as electrons with a definite speed (this means that the corresponding waves have a definite length). It seems the more peculiar because if one

the least distances and energies.

hydrogen atom, which has only one electron orbiting around the nucleus. But it was not clear how one ought to extend it to more complicated atoms. Moreover, the idea of a limited set of allowed orbits seemed very arbitrary. The new theory of quantum mechanics resolved this difficulty. It revealed that an electron orbiting around the nucleus could be thought of as a wave, with a wavelength that depended on its velocity. For certain orbits, the length of the orbit would correspond to a whole number (as opposed to a fractional number) of wavelengths of the electron. For these orbits the wave crest would be in the same position each time round, so the waves would add up: these orbits would correspond to Bohr's allowed orbits. However, for orbits whose lengths were not a whole number of wavelengths, each wave crest would eventually be canceled out by a trough as the electrons went round; these orbits would not be allowed.

A nice way of visualizing the wave/particle duality is the so-called sum over histories introduced by the American scientist Richard Feynman. In this approach the particle is not supposed to have a single history or path in space-time, as it would in a classical, nonquantum theory. Instead it is supposed to go from A to B by every possible path. With each path there are associated a couple of numbers: one represents the size of a wave and the other represents the position in the cycle (i.e., whether it is at a crest or a trough). The probability of going from A to B is found by adding up the waves for all the paths. In general, if one compares a set of neighboring paths, the phases or positions in the cycle will differ greatly. This means that the waves associated with these paths will almost exactly cancel each other out. However, for some sets of neighboring paths the phase will not vary much between paths. The waves for these paths will not cancel out. Such paths correspond to Bohr's allowed orbits.

With these ideas, in concrete mathematical form, it was relatively straightforward to calculate the allowed orbits in more complicated atoms and even in molecules, which are made up of a number of atoms held together by electrons in orbits that go round more than one

molecules. Since the structure of molecules and their reactions with each other underlie all of chemistry and biology, quantum mechanics allows us in principle to predict nearly everything we see around us, within the limits set by the uncertainty principle. (In practice, however, the calculations required for systems containing more than a few electrons are so complicated that we cannot do them.)

Einstein's general theory of relativity seems to govern the large-scale structure of the universe. It is what is called a classical theory; that is, it does not take account of the uncertainty principle of quantum mechanics, as it should for consistency with other theories. The reason that this does not lead to any discrepancy with observation is that all the gravitational fields that we normally experience are very weak. However, the singularity theorems discussed earlier indicate that the gravitational field should get very strong in at least two situations, black holes and the big bang. In such strong fields the effects of quantum mechanics should be important. Thus, in a sense, classical general relativity, by predicting points of infinite density, predicts its own downfall, just as classical (that is, nonquantum) mechanics predicted its downfall by suggesting that atoms should collapse to infinite density. We do not yet have a complete consistent theory that unifies general relativity and quantum mechanics, but we do know a number of the features it should have. The consequences that these would have for black holes and the big bang will be described in later chapters. For the moment, however, we shall turn to the recent attempts to bring together our understanding of the other forces of nature into a single, unified quantum theory.

CHAPTER 5

ELEMENTARY PARTICLES AND THE FORCES OF NATURE

Aristotle believed that all the matter in the universe was made up of four basic elements – earth, air, fire, and water. These elements were acted on by two forces: gravity, the tendency for earth and water to sink, and levity, the tendency for air and fire to rise. This division of the contents of the universe into matter and forces is still used today.

Aristotle believed that matter was continuous, that is, one could divide a piece of matter into smaller and smaller bits without any limit: one never came up against a grain of matter that could not be divided further. A few Greeks, however, such as Democritus, held that matter was inherently grainy and that everything was made up of large numbers of various different kinds of atoms. (The word *atom* means "indivisible" in Greek.) For centuries the argument continued without any real evidence on either side, but in 1803 the British chemist and physicist John Dalton pointed out that the fact that chemical compounds always combined in certain proportions could be explained by the grouping together of atoms to form units called molecules. How

college of which I am now a fellow). He later resigned as Master because of disagreements with the Fellows. There had been a bitter dispute in the college ever since a group of young Fellows returning after the war had voted many of the old Fellows out of the college offices they had held for a long time. This was before my time; I joined the college in 1965 at the tail end of the bitterness, when similar disagreements forced another Nobel Prize–winning Master, Sir Nevill Mott, to resign.

Up to about thirty years ago, it was thought that protons and neutrons were "elementary" particles, but experiments in which protons were collided with other protons or electrons at high speeds indicated that they were in fact made up of smaller particles. These particles were named quarks by the Caltech physicist Murray Gell-Mann, who won the Nobel Prize in 1969 for his work on them. The origin of the name is an enigmatic quotation from James Joyce: "Three quarks for Muster Mark!" The word *quark* is supposed to be pronounced like *quart*, but with a *k* at the end instead of a *t*, but is usually pronounced to rhyme with *lark*.

There are a number of different varieties of quarks: there are six "flavors," which we call up, down, strange, charmed, bottom, and top. The first three flavors had been known since the 1960s but the charmed quark was discovered only in 1974, the bottom in 1977, and the top in 1995. Each flavor comes in three "colors," red, green, and blue. (It should be emphasized that these terms are just labels: quarks are much smaller than the wavelength of visible light and so do not have any color in the normal sense. It is just that modern physicists seem to have more imaginative ways of naming new particles and phenomena—they no longer restrict themselves to Greek!) A proton or neutron is made up of three quarks, one of each color. A proton contains two up quarks and one down quark; a neutron contains two down and one up. We can create particles made up of the other quarks (strange, charmed, bottom, and top), but these all have a much greater mass and decay very rapidly into protons and neutrons.

mechanics tells us that the particles do not have any well-defined axis. What the spin of a particle really tells us is what the particle looks like from different directions. A particle of spin 0 is like a dot: it looks the same from every direction (Fig. 5.1-i). On the other hand, a particle of spin 1 is like an arrow: it looks different from different directions (Fig. 5.1-ii). Only if one turns it round a complete revolution (360 degrees) does the particle look the same. A particle of spin 2 is like a double-headed arrow (Fig. 5.1-iii): it looks the same if one turns it round half a revolution (180 degrees). Similarly, higher spin particles look the same if one turns them through smaller fractions of a complete revolution. All this seems fairly straightforward, but the remarkable fact is that there are particles that do not look the same if one turns them through just one revolution: you have to turn them through two complete revolutions! Such particles are said to have spin ½.

All the known particles in the universe can be divided into two

(i) SPIN = 0

(ii) SPIN = 1

(iii) SPIN = 2

FIGURE 5.1

groups: particles of spin ½, which make up the matter in the universe, and particles of spin 0, 1, and 2, which, as we shall see, give rise to forces between the matter particles. The matter particles obey what is called Pauli's exclusion principle. This was discovered in 1925 by an Austrian physicist, Wolfgang Pauli—for which he received the Nobel Prize in 1945. He was the archetypal theoretical physicist: it was said of him that even his presence in the same town would make experiments go wrong! Pauli's exclusion principle says that two similar particles cannot exist in the same state; that is, they cannot have both the same position and the same velocity, within the limits given by the uncertainty principle. The exclusion principle is crucial because it explains why matter particles do not collapse to a state of very high density under the influence of the forces produced by the particles of spin 0, 1, and 2: if the matter particles have very nearly the same positions, they must have different velocities, which means that they will not stay in the same position for long. If the world had been created without the exclusion principle, quarks would not form separate, well-defined protons and neutrons. Nor would these, together with electrons, form separate, well-defined atoms. They would all collapse to form a roughly uniform, dense "soup."

A proper understanding of the electron and other spin-½ particles did not come until 1928, when a theory was proposed by Paul Dirac, who later was elected to the Lucasian Professorship of Mathematics at Cambridge (the same professorship that Newton had once held and that I now hold). Dirac's theory was the first of its kind that was consistent with both quantum mechanics and the special theory of relativity. It explained mathematically why the electron had spin-½; that is, why it didn't look the same if you turned it through only one complete revolution, but did if you turned it through two revolutions. It also predicted that the electron should have a partner: an anti-electron, or positron. The discovery of the positron in 1932 confirmed Dirac's theory and led to his being awarded the Nobel Prize for physics in 1933. We now know that every particle has an antiparticle, with

which can annihilate with them. (In the case of the force-carrying particles, the antiparticles are the same as the particles themselves.) There could be whole antiworlds and antipeople made out of antiparticles. However, if you meet your antiself, don't shake hands! You would both vanish in a great flash of light. The question of why there seem to be so many more particles than antiparticles around us is extremely important, and I shall return to it later in the chapter.

In quantum mechanics, the forces or interactions between matter particles are all supposed to be carried by particles of integer spin – 0, 1, or 2. What happens is that a matter particle, such as an electron or a quark, emits a force-carrying particle. The recoil from this emission changes the velocity of the matter particle. The force-carrying particle then collides with another matter particle and is absorbed. This collision changes the velocity of the second particle, just as if there had been a force between the two matter particles. It is an important property of the force-carrying particles that they do not obey the exclusion principle. This means that there is no limit to the number that can be exchanged, and so they can give rise to a strong force. However, if the force-carrying particles have a high mass, it will be difficult to produce and exchange them over a large distance. So the forces that they carry will have only a short range. On the other hand, if the force-carrying particles have no mass of their own, the forces will be long range. The force-carrying particles exchanged between matter particles are said to be virtual particles because, unlike "real" particles, they cannot be directly detected by a particle detector. We know they exist, however, because they do have a measurable effect: they give rise to forces between matter particles. Particles of spin 0, 1, or 2 do also exist in some circumstances as real particles, when they can be directly detected. They then appear to us as what a classical physicist would call waves, such as waves of light or gravitational waves. They may sometimes be emitted when matter particles interact with each other by exchanging virtual force-carrying particles. For example, the electric repulsive force between two electrons is due to the exchange of virtual photons,

which can never be directly detected; but if one electron moves past another, real photons may be given off, which we detect as light waves.)

Force-carrying particles can be grouped into four categories according to the strength of the force that they carry and the particles with which they interact. It should be emphasized that this division into four classes is man-made; it is convenient for the construction of partial theories, but it may not correspond to anything deeper. Ultimately, most physicists hope to find a unified theory that will explain all four forces as different aspects of a single force. Indeed, many would say this is the prime goal of physics today. Recently, successful attempts have been made to unify three of the four categories of force – and I shall describe these in this chapter. The question of the unification of the remaining category, gravity, we shall leave till later.

The first category is the gravitational force. This force is universal, that is, every particle feels the force of gravity, according to its mass or energy. Gravity is the weakest of the four forces by a long way; it is so weak that we would not notice it at all were it not for two special properties that it has: it can act over large distances, and it is always attractive. This means that the very weak gravitational forces between the individual particles in two large bodies, such as the earth and the sun, can all add up to produce a significant force. The other three forces are either short range, or are sometimes attractive and sometimes repulsive, so they tend to cancel out. In the quantum mechanical way of looking at the gravitational field, the force between two matter particles is pictured as being carried by a particle of spin 2 called the graviton. This has no mass of its own, so the force that it carries is long range. The gravitational force between the sun and the earth is ascribed to the exchange of gravitons between the particles that make up these two bodies. Although the exchanged particles are virtual, they certainly do produce a measurable effect – they make the earth orbit the sun! Real gravitons make up what classical physicists would call gravitational waves, which are very weak – and so difficult to detect that they have not yet been observed.

[illegible]

the photon, so it is absorbed.

[illegible]

Harvard both proposed theories that unified this interaction with the electromagnetic force, just as Maxwell had unified electricity and magnetism about a hundred years earlier. They suggested that in addition to the photon, there were three other spin-1 particles, known collectively as massive vector bosons, that carried the weak force. These were called W^+ (pronounced W plus), W^- (pronounced W minus), and Z^0 (pronounced Z naught), and each had a mass of around 100 GeV (GeV stands for gigaelectron volt, or one thousand million electron volts). The Weinberg-Salam theory exhibits a property known as spontaneous symmetry breaking. This means that what appear to be a number of completely different particles at low energies are in fact found to be all the same type of particle, only in different states. At high energies all these particles behave similarly. The effect is rather like the behavior of a roulette ball on a roulette wheel. At high energies (when the wheel is spun quickly) the ball behaves in essentially only one way—it rolls round and round. But as the wheel slows, the energy of the ball decreases, and eventually the ball drops into one of the thirty-seven slots in the wheel. In other words, at low energies there are thirty-seven different states in which the ball can exist. If, for some reason, we could only observe the ball at low energies, we would then think that there were thirty-seven different types of ball!

In the Weinberg-Salam theory, at energies much greater than 100 GeV, the three new particles and the photon would all behave in a similar manner. But at the lower particle energies that occur in most normal situations, this symmetry between the particles would be broken. W^+, W^-, and Z^0 would acquire large masses, making the forces they carry have a very short range. At the time that Salam and Weinberg proposed their theory, few people believed them, and particle accelerators were not powerful enough to reach the energies of 100 GeV required to produce real W^+, W^-, or Z^0 particles. However, over the next ten years or so, the other predictions of the theory at lower energies agreed so well with experiment that, in 1979, Salam, Wein-

Weinberg were awarded the Nobel Prize for physics, together with Sheldon Glashow, also at Harvard, who had suggested similar unified theories of the electromagnetic and weak nuclear forces. The Nobel committee was spared the embarrassment of having made a mistake by the discovery in 1983 at CERN (European Centre for Nuclear Research) of the three massive partners of the photon, with the correct predicted masses and other properties. Carlo Rubbia, who led the team of several hundred physicists that made the discovery, received the Nobel Prize in 1984, along with Simon van der Meer, the CERN engineer who developed the antimatter storage system employed. (It is very difficult to make a mark in experimental physics these days unless you are already at the top!)

The fourth category is the strong nuclear force, which holds the quarks together in the proton and neutron, and holds the protons and neutrons together in the nucleus of an atom. It is believed that this force is carried by another spin-1 particle, called the gluon, which interacts only with itself and with the quarks. The strong nuclear force has a curious property called confinement: it always binds particles together into combinations that have no color. One cannot have a single quark on its own because it would have a color (red, green, or blue). Instead, a red quark has to be joined to a green and a blue quark by a "string" of gluons (red + green + blue = white). Such a triplet constitutes a proton or a neutron. Another possibility is a pair consisting of a quark and an antiquark (red + antired, or green + antigreen, or blue + antiblue = white). Such combinations make up the particles known as mesons, which are unstable because the quark and antiquark can annihilate each other, producing electrons and other particles. Similarly, confinement prevents one having a single gluon on its own, because gluons also have color. Instead, one has to have a collection of gluons whose colors add up to white. Such a collection forms an unstable particle called a glueball.

The fact that confinement prevents one from observing an isolated quark or gluon might seem to make the whole notion of quarks and

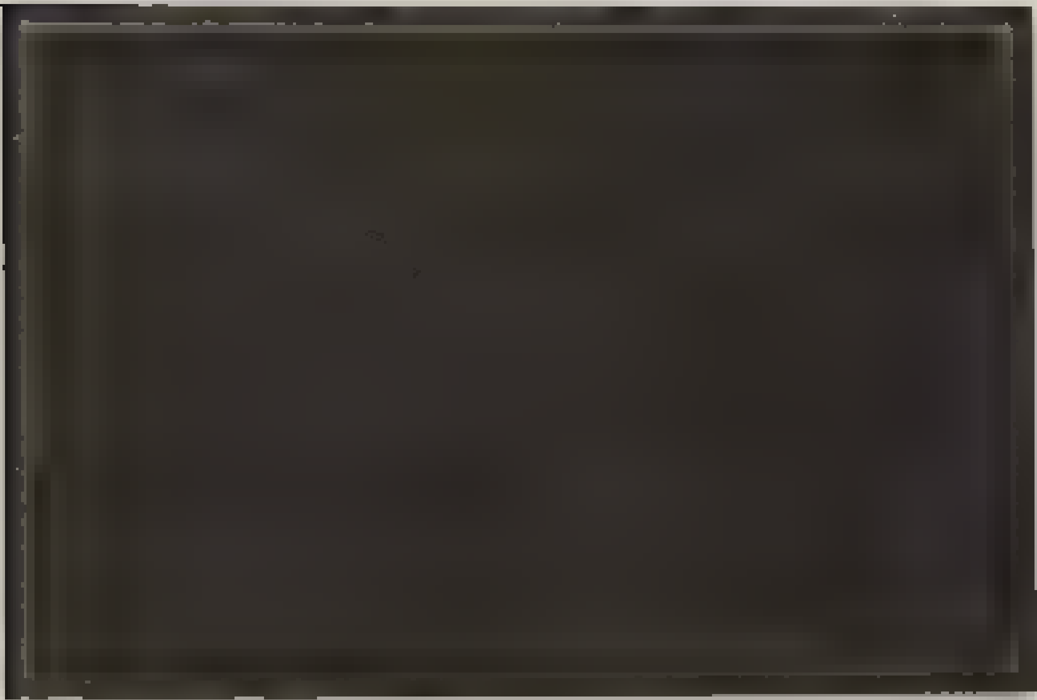

FIGURE 5.2 A proton and an antiproton collide at high energy, producing a couple of almost free quarks.

grand unified theories directly in the laboratory. However, just as in the case of the electromagnetic and weak unified theory, there are low-energy consequences of the theory that can be tested.

The most interesting of these is the prediction that protons, which make up much of the mass of ordinary matter, can spontaneously decay into lighter particles such as antielectrons. The reason this is possible is that at the grand unification energy there is no essential difference between a quark and an antielectron. The three quarks inside a proton normally do not have enough energy to change into antielectrons, but very occasionally one of them may acquire sufficient energy to make the transition because the uncertainty principle means that the energy of the quarks inside the proton cannot be fixed exactly. The proton would then decay. The probability of a quark gaining sufficient energy is so low that one is likely to have to wait at least a million million million million million years (1 followed by thirty zeros). This is much longer than the time since the big bang, which is a mere ten thousand million years or so (1 followed by ten zeros). Thus

one might think that the possibility of spontaneous proton decay could not be tested experimentally. However, one can increase one's chances of detecting a decay by observing a large amount of matter containing a very large number of protons. (If, for example, one observed a number of protons equal to 1 followed by thirty-one zeros for a period of one year, one would expect, according to the simplest GUT, to observe more than one proton decay.)

A number of such experiments have been carried out, but none have yielded definite evidence of proton or neutron decay. One experiment used eight thousand tons of water and was performed in the Morton Salt Mine in Ohio (to avoid other events taking place, caused by cosmic rays, that might be confused with proton decay). Since no spontaneous proton decay had been observed during the experiment, one can calculate that the probable life of the proton must be greater than ten million million million million million years (1 with thirty-one zeros after it). This is longer than the lifetime predicted by the simplest grand unified theory, but there are more elaborate theories in which the predicted lifetimes are longer. Still more sensitive experiments involving even larger quantities of matter will be needed to test them.

Even though it is very difficult to observe spontaneous proton decay, it may be that our very existence is a consequence of the reverse process, the production of protons, or more simply, of quarks, from an initial situation in which there were no more quarks than antiquarks, which is the most natural way to imagine the universe starting out. Matter on the earth is made up mainly of protons and neutrons, which in turn are made up of quarks. There are no antiprotons or antineutrons, made up from antiquarks, except for a few that physicists produce in large particle accelerators. We have evidence from cosmic rays that the same is true for all the matter in our galaxy: there are no antiprotons or antineutrons apart from a small number that are produced as particle/antiparticle pairs in high-energy collisions. If there were large regions of antimatter in our galaxy, we would expect to observe large quantities of radiation from the borders between the regions of matter and

quarks, and quarks antiquarks.)

CHAPTER 6

BLACK HOLES

The term *black hole* is of very recent origin. It was coined in 1969 by the American scientist John Wheeler as a graphic description of an idea that goes back at least two hundred years, to a time when there were two theories about light: one, which Newton favored, was that it was composed of particles; the other was that it was made of waves. We now know that really both theories are correct. By the wave/particle duality of quantum mechanics, light can be regarded as both a wave and a particle. Under the theory that light is made up of waves, it was not clear how it would respond to gravity. But if light is composed of particles, one might expect them to be affected by gravity in the same way that cannonballs, rockets, and planets are. At first people thought that particles of light traveled infinitely fast, so gravity would not have been able to slow them down, but the discovery by Roemer that light travels at a finite speed meant that gravity might have an important effect.

On this assumption, a Cambridge don, John Michell, wrote a paper in 1783 in the *Philosophical Transactions of the Royal Society of London* in

which he pointed out that a star that was sufficiently massive and compact would have such a strong gravitational field that light could not escape: any light emitted from the surface of the star would be dragged back by the star's gravitational attraction before it could get very far. Michell suggested that there might be a large number of stars like this. Although we would not be able to see them because the light from them would not reach us, we would still feel their gravitational attraction. Such objects are what we now call black holes, because that is what they are: black voids in space. A similar suggestion was made a few years later by the French scientist the Marquis de Laplace, apparently independently of Michell. Interestingly enough, Laplace included it in only the first and second editions of his book *The System of the World*, and left it out of later editions; perhaps he decided that it was a crazy idea. (Also, the particle theory of light went out of favor during the nineteenth century; it seemed that everything could be explained by the wave theory, and according to the wave theory, it was not clear that light would be affected by gravity at all.)

In fact, it is not really consistent to treat light like cannonballs in Newton's theory of gravity because the speed of light is fixed. (A cannonball fired upward from the earth will be slowed down by gravity and will eventually stop and fall back; a photon, however, must continue upward at a constant speed. How then can Newtonian gravity affect light?) A consistent theory of how gravity affects light did not come along until Einstein proposed general relativity in 1915. And even then it was a long time before the implications of the theory for massive stars were understood.

To understand how a black hole might be formed, we first need an understanding of the life cycle of a star. A star is formed when a large amount of gas (mostly hydrogen) starts to collapse in on itself due to its gravitational attraction. As it contracts, the atoms of the gas collide with each other more and more frequently and at greater and greater speeds—the gas heats up. Eventually, the gas will be so hot that when the hydrogen atoms collide they no longer bounce off each other, but

of gravity and the repulsion that arises from the exclusion principle, just as earlier in its life gravity was balanced by the heat.

Chandrasekhar realized, however, that there is a limit to the repulsion that the exclusion principle can provide. The theory of relativity limits the maximum difference in the velocities of the matter particles in the star to the speed of light. This means that when the star got sufficiently dense, the repulsion caused by the exclusion principle would be less than the attraction of gravity. Chandrasekhar calculated that a cold star of more than about one and a half times the mass of the sun would not be able to support itself against its own gravity. (This mass is now known as the Chandrasekhar limit.) A similar discovery was made about the same time by the Russian scientist Lev Davidovich Landau.

This had serious implications for the ultimate fate of massive stars. If a star's mass is less than the Chandrasekhar limit, it can eventually stop contracting and settle down to a possible final state as a "white dwarf" with a radius of a few thousand miles and a density of hundreds of tons per cubic inch. A white dwarf is supported by the exclusion principle repulsion between the electrons in its matter. We observe a large number of these white dwarf stars. One of the first to be discovered is a star that is orbiting around Sirius, the brightest star in the night sky.

Landau pointed out that there was another possible final state for a star, also with a limiting mass of about one or two times the mass of the sun but much smaller even than a white dwarf. These stars would be supported by the exclusion principle repulsion between neutrons and protons, rather than between electrons. They were therefore called neutron stars. They would have a radius of only ten miles or so and a density of hundreds of millions of tons per cubic inch. At the time they were first predicted, there was no way that neutron stars could be observed. They were not actually detected until much later.

Stars with masses above the Chandrasekhar limit, on the other hand, have a big problem when they come to the end of their fuel. In some cases they may explode or manage to throw off enough matter to

reduce their mass below the limit and so avoid catastrophic gravitational collapse. But it was hard to believe that this always happened, no matter how big the star. How would it know that it had to lose weight? And even if every star managed to lose enough mass to avoid collapse, what would happen if you added more mass to a white dwarf or neutron star to take it over the limit? Would it collapse to infinite density? Eddington was shocked by that implication, and he refused to believe Chandrasekhar's result. Eddington thought it was simply not possible that a star could collapse to a point. This was the view of most scientists: Einstein himself wrote a paper in which he claimed that stars would not shrink to zero size. The hostility of other scientists, particularly Eddington, his former teacher and the leading authority on the structure of stars, persuaded Chandrasekhar to abandon this line of work and turn instead to other problems in astronomy, such as the motion of star clusters. However, when he was awarded the Nobel Prize in 1983, it was, at least in part, for his early work on the limiting mass of cold stars.

Chandrasekhar had shown that the exclusion principle could not halt the collapse of a star more massive than the Chandrasekhar limit, but the problem of understanding what would happen to such a star, according to general relativity, was first solved by a young American, Robert Oppenheimer, in 1939. His result, however, suggested that there would be no observational consequences that could be detected by the telescopes of the day. Then World War II intervened and Oppenheimer himself became closely involved in the atom bomb project. After the war the problem of gravitational collapse was largely forgotten as most scientists became caught up in what happens on the scale of the atom and its nucleus. In the 1960s, however, interest in the large-scale problems of astronomy and cosmology was revived by a great increase in the number and range of astronomical observations brought about by the application of modern technology. Oppenheimer's work was then rediscovered and extended by a number of people.

The picture that we now have from Oppenheimer's work is as follows. The gravitational field of the star changes the paths of light rays in space-time from what they would have been had the star not been present. The light cones, which indicate the paths followed in space and time by flashes of light emitted from their tips, are bent slightly inward near the surface of the star. This can be seen in the bending of light from distant stars observed during an eclipse of the sun. As the star contracts, the gravitational field at its surface gets stronger and the light cones bend inward more. This makes it more difficult for light from the star to escape, and the light appears dimmer and redder to an observer at a distance. Eventually, when the star has shrunk to a certain critical radius, the gravitational field at the surface becomes so strong that the light cones are bent inward so much that light can no longer escape (Fig. 6.1). According to the theory of relativity, nothing can travel faster than light. Thus if light cannot escape, neither can anything else; everything is dragged back by the gravitational field. So one has a set of events, a region of space-time, from which it is not possible to escape to reach a distant observer. This region is what we now call a black hole. Its boundary is called the event horizon and it coincides with the paths of light rays that just fail to escape from the black hole.

In order to understand what you would see if you were watching a star collapse to form a black hole, one has to remember that in the theory of relativity there is no absolute time. Each observer has his own measure of time. The time for someone on a star will be different from that for someone at a distance, because of the gravitational field of the star. Suppose an intrepid astronaut on the surface of the collapsing star, collapsing inward with it, sent a signal every second, according to his watch, to his spaceship orbiting about the star. At some time on his watch, say 11:00, the star would shrink below the critical radius at which the gravitational field becomes so strong nothing can escape, and his signals would no longer reach the spaceship. As 11:00 approached his companions watching from the spaceship would [illegible] nervous

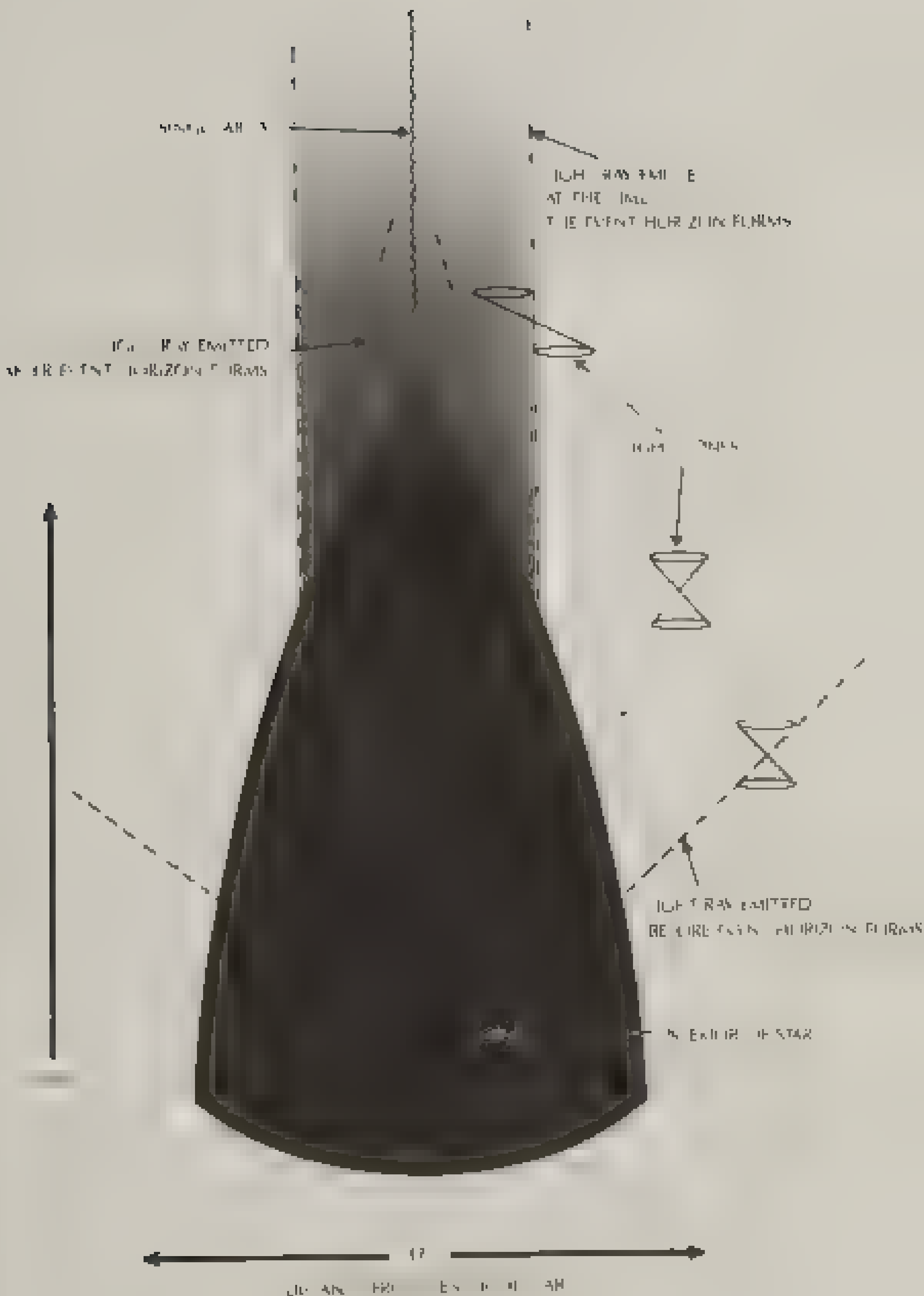

FIGURE 6.1

are from the star, so the gravitational force on our intrepid astronaut's

[illegible] in realistic situations.

[illegible] of infinite density and the end of time.

[illegible]

[illegible]

produces gravitational waves. The effect of the energy loss will be to change the orbit of the earth so that gradually it gets nearer and nearer to the sun, eventually collides with it, and settles down to a stationary state. The rate of energy loss in the case of the earth and the sun is very low—about enough to run a small electric heater. This means it will take about a thousand million million million million years for the earth to run into the sun, so there's no immediate cause for worry! The change in the orbit of the earth is too slow to be observed, but this same effect has been observed over the past few years occurring in the system called PSR 1913 + 16 (PSR stands for "pulsar," a special type of neutron star that emits regular pulses of radio waves). This system contains two neutron stars orbiting each other, and the energy they are losing by the emission of gravitational waves is causing them to spiral in toward each other. This confirmation of general relativity won J. H. Taylor and R. A. Hulse the Nobel Prize in 1993. It will take about three hundred million years for them to collide. Just before they do, they will be orbiting so fast that they will emit enough gravitational waves for detectors like LIGO to pick up.

During the gravitational collapse of a star to form a black hole, the movements would be much more rapid, so the rate at which energy is carried away would be much higher. It would therefore not be too long before it settled down to a stationary state. What would this final stage look like? One might suppose that it would depend on all the complex features of the star from which it had formed—not only its mass and rate of rotation, but also the different densities of various parts of the star, and the complicated movements of the gases within the star. And if black holes were as varied as the objects that collapsed to form them, it might be very difficult to make any predictions about black holes in general.

In 1967, however, the study of black holes was revolutionized by Werner Israel, a Canadian scientist (who was born in Berlin, brought up in South Africa, and took his doctoral degree in Ireland).

showed that, according to general relativity, non-rotating black holes must be very simple; they were perfectly spherical, their size depended only on their mass, and any two such black holes with the same mass were identical. They could, in fact, be described by a particular solution of Einstein's equations that had been known since 1917, found by Karl Schwarzschild shortly after the discovery of general relativity. At first many people, including Israel himself, argued that since black holes had to be perfectly spherical, a black hole could only form from the collapse of a perfectly spherical object. Any real star—which would never be perfectly spherical—could therefore only collapse to form a naked singularity.

There was, however, a different interpretation of Israel's result, which was advocated by Roger Penrose and John Wheeler in particular. They argued that the rapid movements involved in a star's collapse would mean that the gravitational waves it gave off would make it ever more spherical, and by the time it had settled down to a stationary state, it would be precisely spherical. According to this view, any non-rotating star, however complicated its shape and internal structure, would end up after gravitational collapse as a perfectly spherical black hole, whose size would depend only on its mass. Further calculations supported this view, and it soon came to be adopted generally.

Israel's result dealt with the case of black holes formed from non-rotating bodies only. In 1963, Roy Kerr, a New Zealander, found a set of solutions of the equations of general relativity that described rotating black holes. These "Kerr" black holes rotate at a constant rate, their size and shape depending only on their mass and rate of rotation. If the rotation is zero, the black hole is perfectly round and the solution is identical to the Schwarzschild solution. If the rotation is non-zero, the black hole bulges outward near its equator (just as the earth or the sun bulge due to their rotation), and the faster it rotates, the more it bulges. So, to extend Israel's result to include rotating bodies, it was conjectured that any rotating body that collapsed to form a black hole would eventually settle down to a stationary state described by the Kerr solution.

[illegible]

opponents of black holes: [illegible]

the only evidence was [illegible]

field if it had been a gravitational red shift, the object would have to be so massive and so near to us that it would disturb the orbits of planets in the Solar System. This suggested that the red shift was instead caused by the expansion of the universe, which, in turn, meant that the object was a very long distance away. And to be visible at such a great distance, the object must be very bright, must, in other words, be emitting a huge amount of energy. The only mechanism that people could think of that would produce such large quantities of energy seemed to be the gravitational collapse not just of a star but of a whole central region of a galaxy. A number of other similar "quasi-stellar objects," or quasars, have been discovered, all with large red shifts. But they are all too far away and therefore too difficult to observe to provide conclusive evidence of black holes.

Further encouragement for the existence of black holes came in 1967 with the discovery by a research student at Cambridge, Jocelyn Bell, of objects in the sky that were emitting regular pulses of radio waves. At first Bell and her supervisor, Antony Hewish, thought they might have made contact with an alien civilization in the galaxy! Indeed, at the seminar at which they announced their discovery, I remember that they called the first four sources to be found LGM 1–4, LGM standing for "Little Green Men." In the end, however, they and everyone else came to the less romantic conclusion that these objects, which were given the name pulsars, were in fact rotating neutron stars that were emitting pulses of radio waves because of a complicated interaction between their magnetic fields and surrounding matter. This was bad news for writers of space westerns, but very hopeful for the small number of us who believed in black holes at that time: it was the first positive evidence that neutron stars existed. A neutron star has a radius of about ten miles, only a few times the critical radius at which a star becomes a black hole. If a star could collapse to such a small size, it is not unreasonable to expect that other stars could collapse to even smaller size and become black holes.

How could we hope to detect a black hole, as by its very definition it

FIGURE 6.2 The brighter of the two stars near the center of the photograph is Cygnus X-1, which is thought to consist of a black hole and a normal star, orbiting around each other.

evidence in favor of black holes that I have conceded the bet. I paid the specified penalty, which was a one-year subscription to *Penthouse*, to the outrage of Kip's liberated wife.

We also now have evidence for several other black holes in systems like Cygnus X-1 in our galaxy and in two neighboring galaxies called the Magellanic Clouds. The number of black holes, however, is almost certainly very much higher; in the long history of the universe, many stars must have burned all their nuclear fuel and have had to collapse. The number of black holes may well be greater even than the number of visible stars, which totals about a hundred thousand million in our galaxy alone. The extra gravitational attraction of such a large number of black holes could explain why our galaxy rotates at the rate it does: the mass of the visible stars is insufficient to account for this. We also have some evidence that there is a much larger black hole, with a mass of about a hundred thousand times that of the sun, at the center of our galaxy. Stars in the galaxy that come too near this black hole will be

FIGURE 6.3

torn apart by the difference in the gravitational forces on their near and far sides. Their remains, and gas that is thrown off other stars, will fall toward the black hole. As in the case of Cygnus X-1, the gas will spiral inward and will heat up, though not as much as in that case. It will not get hot enough to emit X rays, but it could account for the very compact source of radio waves and infrared rays that is observed at the galactic center.

It is thought that similar but even larger black holes, with masses of about a hundred million times the mass of the sun, occur at the centers of quasars. For example, observations with the Hubble telescope of the galaxy known as M87 reveal that it contains a disk of gas 130 light-years across rotating about a central object two thousand million times the mass of the sun. This can only be a black hole. Matter falling into such a supermassive black hole would provide the only source of power great enough to explain the enormous amounts of energy that

together in stars and galaxies.

holes. If there are now, we would learn a lot about the very early stages of the universe. Primordial black holes with masses more than a thousand million tons (the mass of a large mountain) could be detected only by their gravitational influence on other, visible matter or on the expansion of the universe. However, as we shall learn in the next chapter, black holes are not really black after all: they glow like a hot body, and the smaller they are, the more they glow. So, paradoxically, smaller black holes might actually turn out to be easier to detect than large ones!

CHAPTER 7

BLACK HOLES AIN'T SO BLACK

Before 1970, my research on general relativity had concentrated mainly on the question of whether or not there had been a big bang singularity. However, one evening in November that year, shortly after the birth of my daughter, Lucy, I started to think about black holes as I was getting into bed. My disability makes this rather a slow process, so I had plenty of time. At that date there was no precise definition of which points in space-time lay inside a black hole and which lay outside. I had already discussed with Roger Penrose the idea of defining a black hole as the set of events from which it was not possible to escape to a large distance, which is now the generally accepted definition. It means that the boundary of the black hole, the event horizon, is formed by the light rays that just fail to escape from the black hole, hovering forever just on the edge (Fig. 7.1). It is a bit like running away from the police and just managing to keep one step ahead but not being able to get clear away!

Suddenly I realized that the paths of these light rays could never approach one another. If they did, they must eventually run into one

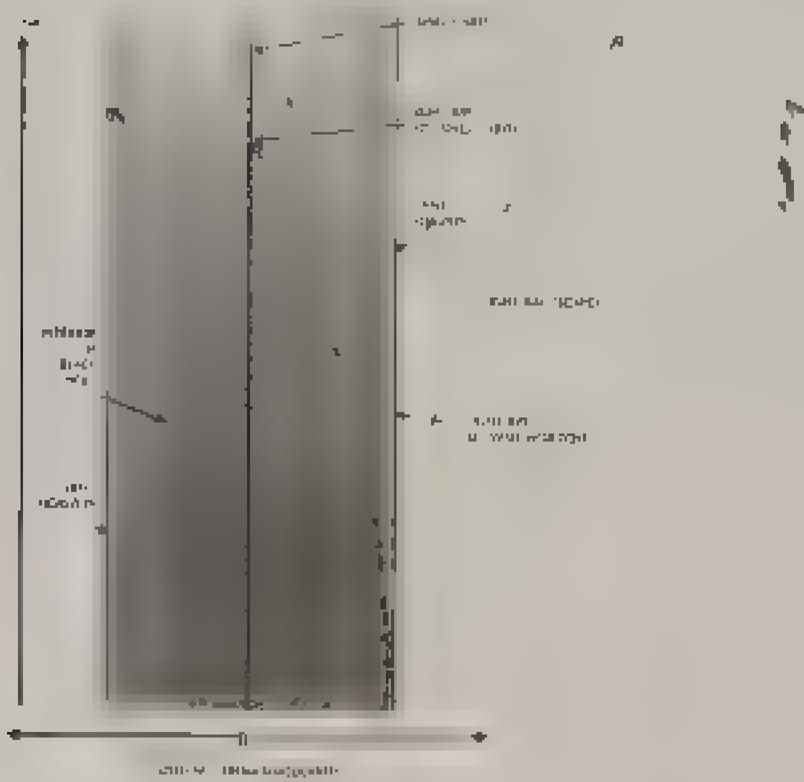

FIGURE 7.1

another. It would be like meeting someone else running away from the police in the opposite direction—you would both be caught! (Or, in this case, fall into a black hole.) But if these light rays were swallowed up by the black hole, then they could not have been on the boundary of the black hole. So the paths of light rays in the event horizon had always to be moving parallel to, or away from, each other. Another way of seeing this is that the event horizon, the boundary of the black hole, is like the edge of a shadow—the shadow of impending doom. If you look at the shadow cast by a source at a great distance, such as the sun, you will see that the rays of light in the edge are not approaching each other.

If the rays of light that form the event horizon, the boundary of the black hole, can never approach each other, the area of the event horizon might stay the same or increase with time, but it could never decrease because that would mean that at least some of the rays of light

on the boundary would have to be approaching each other. In fact, the area would increase whenever matter or radiation fell into the black hole (Fig. 7.2). Or if two black holes collided and merged together to form a single black hole, the area of the event horizon of the final black hole would be greater than or equal to the sum of the areas of the event horizons of the original black holes (Fig. 7.3). This nondecreasing property of the event horizon's area placed an important restriction on the possible behavior of black holes. I was so excited with my discovery that I did not get much sleep that night. The next day I rang up Roger Penrose. He agreed with me. I think, in fact, that he had been aware of this property of the area. However, he had been using a slightly different definition of a black hole. He had not realized that the

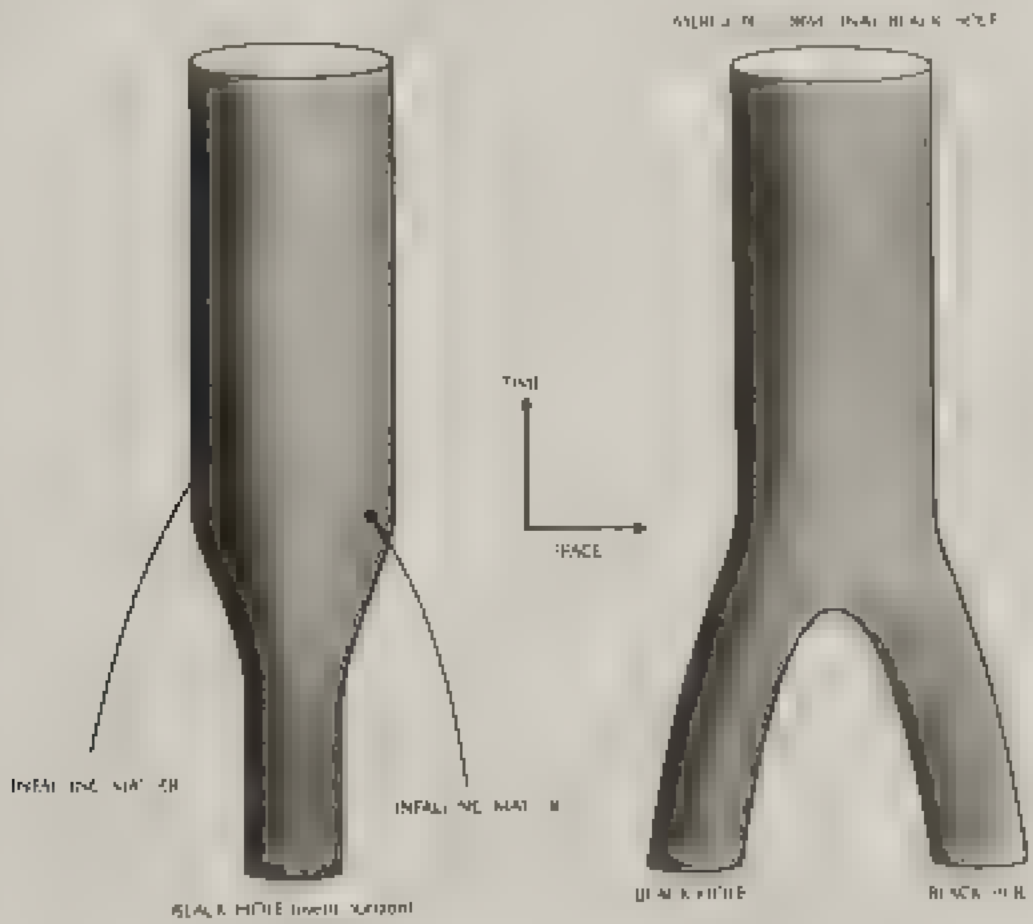

FIGURE 7.2 AND FIGURE 7.3

probable state would be a fairly un[illegible] nitrogen molecules throughout the two boxes. [illegible] ordered, and hence have more entropy than [illegible] separate boxes.

The second law of thermodynamics [illegible] than that of other laws [illegible] such as Newton's [illegible] example, because it does not [illegible] always [illegible] cases. The probability of all the gas molecules [illegible] found in one half of the box at a later time [illegible] to one [illegible] can happen. However, if [illegible] there seems to be a rather easier way [illegible] throw some matter with a lot of entropy, such as [illegible] black hole. The total entropy of matter outside [illegible] down, but one could, of course, still say that the [illegible] the entropy inside the black hole, has not [illegible] is no way to look inside the [illegible] entropy the matter inside it has. It would [illegible] some feature of the black hole by which [illegible] would tell its entropy, and which would [illegible] carrying entropy fell into the black hole [illegible] [illegible] matter fell into a black hole, a research [illegible] [illegible] Bekenstein suggested that the area [illegible] measure of the entropy of the black hole [illegible] fell into a black hole, the area [illegible] the sum of the entropy of matter outside black [illegible] horizons would never go down.

This suggestion seemed to [illegible] dynamics from being violated [illegible] one fatal flaw. If a black hole has entropy [illegible] temperature. But a body with a particular temperature [illegible] radiation at a certain rate. It is a matter of [illegible] one heats up a poker in a fire it glows red [illegible]

mass, the lower the temperature

matter particles, such as electrons or quarks. In this case, however, one member of the pair will be a particle and the other an antiparticle (the antiparticles of light and gravity are the same as the particles themselves).

Because energy cannot be created out of nothing, one of the partners in a particle/antiparticle pair will have positive energy, and the other partner negative energy. The one with negative energy is condemned to be a short-lived virtual particle because real particles always have positive energy in normal situations. It must therefore seek out its partner and annihilate with it. However, a real particle close to a massive body has less energy than if it were far away, because it would take energy to lift it far away against the gravitational attraction of the body. Normally, the energy of the particle is still positive, but the gravitational field inside a black hole is so strong that even a real particle can have negative energy there. It is therefore possible, if a black hole is present, for the virtual particle with negative energy to fall into the black hole and become a real particle or antiparticle. In this case it no longer has to annihilate with its partner. Its forsaken partner may fall into the black hole as well. Or, having positive energy, it might also escape from the vicinity of the black hole as a real particle or antiparticle (Fig. 7.4). To an observer at a distance, it will appear to have been emitted from the black hole. The smaller the black hole, the shorter the distance the particle with negative energy will have to go before it becomes a real particle, and thus the greater the rate of emission, and the apparent temperature, of the black hole.

The positive energy of the outgoing radiation would be balanced by a flow of negative energy particles into the black hole. By Einstein's equation $E = mc^2$ (where E is energy, m is mass, and c is the speed of light), energy is proportional to mass. A flow of negative energy into the black hole therefore reduces its mass. As the black hole loses mass, the area of its event horizon gets smaller, but this decrease in the entropy of the black hole is more than compensated for by the entropy of the emitted radiation, so the second law is never violated.

Moreover, the lower the mass of the black hole, the higher its

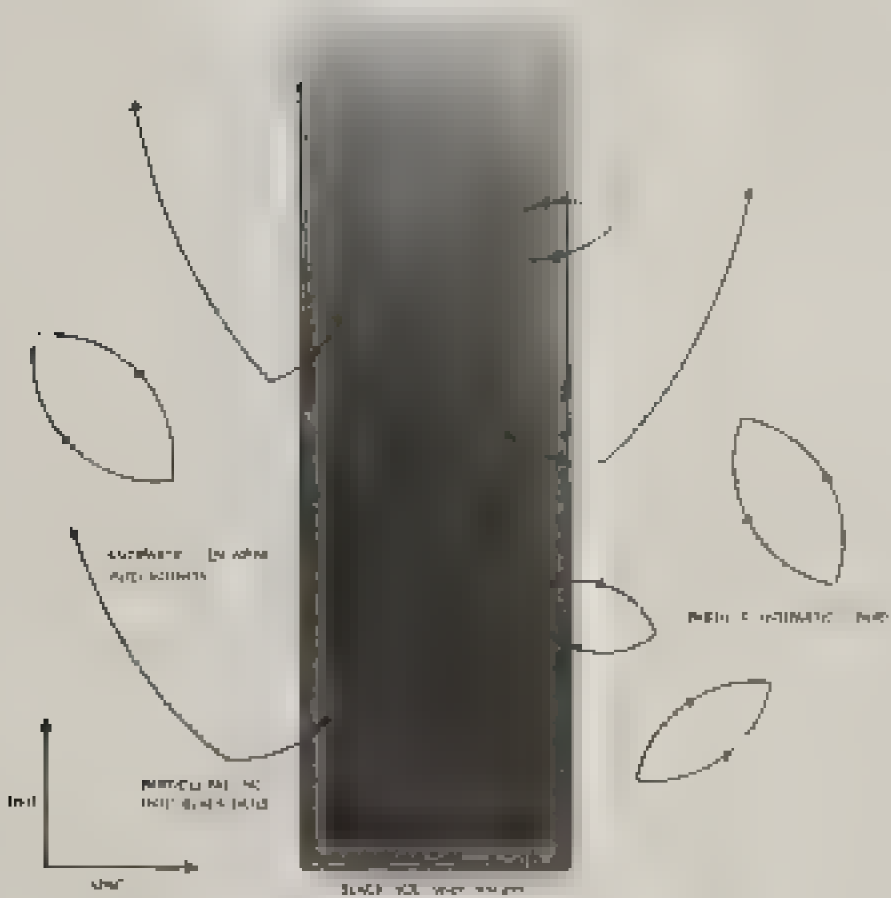

FIGURE 7.4

temperature. So as the black hole loses mass, its temperature and rate of emission increase, so it loses mass more quickly. What happens when the mass of the black hole eventually becomes extremely small is not quite clear, but the most reasonable guess is that it would disappear completely in a tremendous final burst of emission, equivalent to the explosion of millions of H-bombs.

A black hole with a mass a few times that of the sun would have a temperature of only one ten millionth of a degree above absolute zero. This is much less than the temperature of the microwave radiation that fills the universe (about 2.7° above absolute zero), so such black holes would emit even less than they absorb. If the universe is destined to go on expanding forever, the temperature of the microwave radiation will eventually decrease to less than that of such a black hole, which will

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about ten thousand megawatts.

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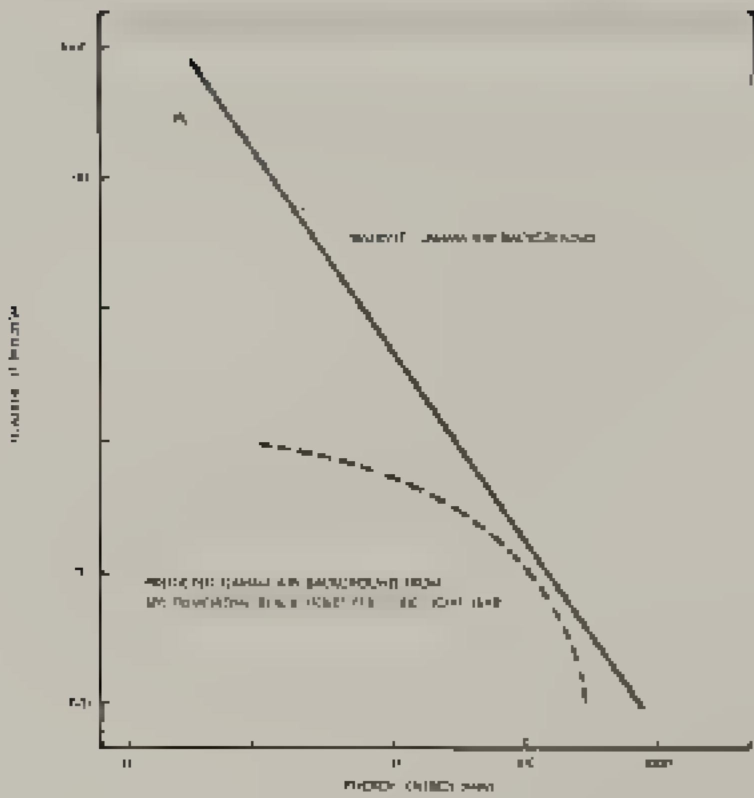

FIGURE 7.5

quantum principle tells us that each gamma ray quantum has a very high energy, because gamma rays have a very high frequency, so it would not take many quanta to radiate even ten thousand megawatts. And to observe these few coming from the distance of Pluto would require a larger gamma ray detector than any that have been constructed so far. Moreover, the detector would have to be in space, because gamma rays cannot penetrate the atmosphere.

Of course, if a black hole as close as Pluto were to reach the end of its life and blow up, it would be easy to detect the final burst of emission. But if the black hole has been emitting for the last ten or twenty thousand million years, the chance of it reaching the end of its life within the next few years, rather than several million years in the past or future, is really rather small! So in order to have a reasonable chance of seeing an explosion before your research grant ran out, you would have to find a way to detect any explosions within a distance of about

to a large extent I was greeted with general incredulity. At the end of my talk the chairman of the session, John G. Taylor from Kings College, London, claimed it was all nonsense. He even wrote a paper to that effect. However, in the end most people, including John Taylor, have come to the conclusion that black holes must radiate like hot bodies if our other ideas about general relativity and quantum mechanics are correct. Thus, even though we have not yet managed to find a primordial black hole, there is fairly general agreement that if we did, it would have to be emitting a lot of gamma rays and X rays.

The existence of radiation from black holes seems to imply that gravitational collapse is not as final and irreversible as we once thought. If an astronaut falls into a black hole, its mass will increase, but eventually the energy equivalent of that extra mass will be returned to the universe in the form of radiation. Thus, in a sense, the astronaut will be "recycled." It would be a poor sort of immortality, however, because any personal concept of time for the astronaut would almost certainly come to an end as he was torn apart inside the black hole! Even the types of particles that were eventually emitted by the black hole would in general be different from those that made up the astronaut: the only feature of the astronaut that would survive would be his mass or energy.

The approximations I used to derive the emission from black holes should work well when the black hole has a mass greater than a fraction of a gram. However, they will break down at the end of the black hole's life when its mass gets very small. The most likely outcome seems to be that the black hole will just disappear, at least from our region of the universe, taking with it the astronaut and any singularity there might be inside it, if indeed there is one. This was the first indication that quantum mechanics might remove the singularities that were predicted by general relativity. However, the methods that I and other people were using in 1974 were not able to answer questions such as whether singularities would occur in quantum gravity. From 1975 onward I therefore started to develop a more powerful approach

to quantum gravity based on Richard Feynman's idea of a sum over histories. The answers that this approach suggests for the origin and fate of the universe and its contents, such as astronauts, will be described in the next two chapters. We shall see that although the uncertainty principle places limitations on the accuracy of all our predictions, it may at the same time remove the fundamental unpredictability that occurs at a space-time singularity.

C H A P T E R 8

THE ORIGIN AND FATE OF THE UNIVERSE

Einstein's general theory of relativity, on its own, predicted that space-time began at the big bang singularity and would come to an end either at the big crunch singularity (if the whole universe recollapsed), or at a singularity inside a black hole (if a local region, such as a star, were to collapse). Any matter that fell into the hole would be destroyed at the singularity, and only the gravitational effect of its mass would continue to be felt outside. On the other hand, when quantum effects were taken into account, it seemed that the mass or energy of the matter would eventually be returned to the rest of the universe, and that the black hole, along with any singularity inside it, would evaporate away and finally disappear. Could quantum mechanics have an equally dramatic effect on the big bang and big crunch singularities? What really happens during the very early or late stages of the universe, when gravitational fields are so strong that quantum effects cannot be ignored? Does the universe in fact have a beginning or an end? And if so, what are they like?

Throughout the 1970s I had been mainly studying black holes, but

in 1981, my interest in questions about the origin and fate of the universe was reawakened when I attended a conference on cosmology organized by the Jesuits in the Vatican. The Catholic Church had made a bad mistake with Galileo when it tried to lay down the law on a question of science, declaring that the sun went round the earth. Now, centuries later, it had decided to invite a number of experts to advise it on cosmology. At the end of the conference the participants were granted an audience with the Pope. He told us that it was all right to study the evolution of the universe after the big bang, but we should not inquire into the big bang itself because that was the moment of Creation and therefore the work of God. I was glad then that he did not know the subject of the talk I had just given at the conference—the possibility that space-time was finite but had no boundary, which means that it had no beginning, no moment of Creation. I had no desire to share the fate of Galileo, with whom I feel a strong sense of identity, partly because of the coincidence of having been born exactly 300 years after his death!

In order to explain the ideas that I and other people have had about how quantum mechanics may affect the origin and fate of the universe, it is necessary first to understand the generally accepted history of the universe, according to what is known as the "hot big bang model." This assumes that the universe is described by a Friedmann model, right back to the big bang. In such models one finds that as the universe expands, any matter or radiation in it gets cooler. (When the universe doubles in size, its temperature falls by half.) Since temperature is simply a measure of the average energy—or speed—of the particles, this cooling of the universe would have a major effect on the matter in it. At very high temperatures, particles would be moving around so fast that they could escape any attraction toward each other due to nuclear or electromagnetic forces, but as they cooled off one would expect particles that attract each other to start to clump together. Moreover, even the types of particles that exist in the universe would depend on the temperature. At high enough temperatures, particles have so much

production

and cause it to collapse again.

[illegible]

nuclei of ord nary hydrogen atoms

[illegible]

have no overall rotation

energy as heat and light. More massive stars would need to be hotter to balance their stronger gravitational attraction, making the nuclear fusion reactions proceed so much more rapidly that they would use up their hydrogen in as little as a hundred million years. They would then contract slightly, and as they heated up further, would start to convert helium into heavier elements like carbon or oxygen. This, however, would not release much more energy, so a crisis would occur, as was described in the chapter on black holes. What happens next is not completely clear, but it seems likely that the central regions of the star would collapse to a very dense state, such as a neutron star or black hole. The outer regions of the star may sometimes get blown off in a tremendous explosion called a supernova, which would outshine all the other stars in its galaxy. Some of the heavier elements produced near the end of the star's life would be flung back into the gas in the galaxy, and would provide some of the raw material for the next generation of stars. Our own sun contains about 2 percent of these heavier elements, because it is a second- or third-generation star, formed some five billion years ago out of a cloud of rotating gas containing the debris of earlier supernovas. Most of the gas in that cloud went to form the sun or got blown away, but a small amount of the heavier elements collected together to form the bodies that now orbit the sun as planets like the earth.

The earth was initially very hot and without an atmosphere. In the course of time it cooled and acquired an atmosphere from the emission of gases from the rocks. This early atmosphere was not one in which we could have survived. It contained no oxygen, but a lot of other gases that are poisonous to us, such as hydrogen sulfide (the gas that gives rotten eggs their smell). There are, however, other primitive forms of life that can flourish under such conditions. It is thought that they developed in the oceans, possibly as a result of chance combinations of atoms into large structures, called macromolecules, which were capable of assembling other atoms in the ocean into similar structures. They would thus have reproduced themselves and multiplied. In some cases

there would be errors in the reproduction. Mostly these errors would have been such that the new macromolecule could not reproduce itself and eventually would have been destroyed. However, a few of the errors would have produced new macromolecules that were even better at reproducing themselves. They would have therefore had an advantage and would have tended to replace the original macromolecules. In this way a process of evolution was started that led to the development of more and more complicated self-reproducing organisms. The first primitive forms of life consumed various materials, including hydrogen sulfide, and released oxygen. This gradually changed the atmosphere to the composition that it has today, and allowed the development of higher forms of life such as fish, reptiles, mammals, and ultimately the human race.

This picture of a universe that started off very hot and cooled as it expanded is in agreement with all the observational evidence that we have today. Nevertheless, it leaves a number of important questions unanswered:

1. Why was the early universe so hot?
2. Why is the universe so uniform on a large scale? Why does it look the same at all points of space and in all directions? In particular, why is the temperature of the microwave background radiation so nearly the same when we look in different directions? It is a bit like asking a number of students an exam question. If they all give exactly the same answer, you can be pretty sure they have communicated with each other. Yet, in the model described above, there would not have been time since the big bang for light to get from one distant region to another, even though the regions were close together in the early universe. According to the theory of relativity, if light cannot get from one region to another, no other information can. So there would be no way in which different regions in the early universe could have come to have the same tempera-

ture as each other, unless for some unexplained reason they happened to start out with the same temperature.

3. Why did the universe start out with so nearly the critical rate of expansion that separates models that recollapse from those that go on expanding forever, that even now, ten thousand million years later, it is still expanding at nearly the critical rate? If the rate of expansion one second after the big bang had been smaller by even one part in a hundred thousand million million, the universe would have recollapsed before it ever reached its present size.
4. Despite the fact that the universe is so uniform and homogeneous on a large scale, it contains local irregularities, such as stars and galaxies. These are thought to have developed from small differences in the density of the early universe from one region to another. What was the origin of these density fluctuations?

The general theory of relativity, on its own, cannot explain these features or answer these questions because of its prediction that the universe started off with infinite density at the big bang singularity. At the singularity, general relativity and all other physical laws would break down: one couldn't predict what would come out of the singularity. As explained before, this means that one might as well cut the big bang, and any events before it, out of the theory, because they can have no effect on what we observe. Space-time *would* have a boundary—a beginning at the big bang.

Science seems to have uncovered a set of laws that, within the limits set by the uncertainty principle, tell us how the universe will develop with time, if we know its state at any one time. These laws may have originally been decreed by God, but it appears that he has since left the universe to evolve according to them and does not now intervene in it. But how did he choose the initial state or configuration of the universe? What were the "boundary conditions" at the beginning of time?

One possible answer is to say that God chose the initial configuration of the universe for reasons that we cannot hope to understand. This would certainly have been within the power of an omnipotent being, but if he had started it off in such an incomprehensible way, why did he choose to let it evolve according to laws that we could understand? The whole history of science has been the gradual realization that events do not happen in an arbitrary manner, but that they reflect a certain underlying order, which may or may not be divinely inspired. It would be only natural to suppose that this order should apply not only to the laws, but also to the conditions at the boundary of space-time that specify the initial state of the universe. There may be a large number of models of the universe with different initial conditions that all obey the laws. There ought to be some principle that picks out one initial state, and hence one model, to represent our universe.

One such possibility is what are called chaotic boundary conditions. These implicitly assume either that the universe is spatially infinite or that there are infinitely many universes. Under chaotic boundary conditions, the probability of finding any particular region of space in any given configuration just after the big bang is the same, in some sense, as the probability of finding it in any other configuration: the initial state of the universe is chosen purely randomly. This would mean that the early universe would have probably been very chaotic and irregular because there are many more chaotic and disordered configurations for the universe than there are smooth and ordered ones. (If each configuration is equally probable, it is likely that the universe started out in a chaotic and disordered state, simply because there are so many more of them.) It is difficult to see how such chaotic initial conditions could have given rise to a universe that is so smooth and regular on a large scale as ours is today. One would also have expected the density fluctuations in such a model to have led to the formation of many more primordial black holes than the upper limit that has been set by observations of the gamma ray background.

If the universe is indeed spatially infinite, or if there are infinitely many

many universes, there would probably be some large regions somewhere where the universe started in a smooth and uniform manner. It is a bit like the well-known horde of monkeys hammering away on typewriters—most of what they write will be garbage, but very occasionally by pure chance they will type out one of Shakespeare's sonnets. Similarly, in the case of the universe, could it be that we are living in a region that just happens by chance to be smooth and uniform? At first sight this might seem very improbable, because such smooth regions would be heavily outnumbered by chaotic and irregular regions. However, suppose that only in the smooth regions were galaxies and stars formed and were conditions right for the development of complicated self-replicating organisms like ourselves who were capable of asking the question: why is the universe so smooth? This is an example of the application of what is known as the anthropic principle, which can be paraphrased as "We see the universe the way it is because we exist."

There are two versions of the anthropic principle, the weak and the strong. The weak anthropic principle states that in a universe that is large or infinite in space and/or time, the conditions necessary for the development of intelligent life will be met only in certain regions that are limited in space and time. The intelligent beings in these regions should therefore not be surprised if they observe that their locality in the universe satisfies the conditions that are necessary for their existence. It is a bit like a rich person living in a wealthy neighborhood not seeing any poverty.

One example of the use of the weak anthropic principle is to "explain" why the big bang occurred about ten thousand million years ago—it takes about that long for intelligent beings to evolve. As explained above, an early generation of stars first had to form. These stars converted some of the original hydrogen and helium into elements like carbon and oxygen, out of which we are made. The stars then exploded as supernovas, and their debris went to form other stars and planets, among them those of our Solar System, which is about five thousand million years old. The first one or two thousand million years

time back to the big bang

for the strong anthropic pr

scale.

only a tiny fraction of a second

breaks water's symmetry.

of the universe was very carefully chosen

energy of the universe is zero.

Now twice zero is also zero. Thus the universe can double the amount of positive matter energy and also double the negative gravitational energy without violation of the conservation of energy. This does not happen in the normal expansion of the universe in which the matter energy density goes down as the universe gets bigger. It does happen, however, in the inflationary expansion because the energy density of the supercooled state remains constant while the universe expands: when the universe doubles in size, the positive matter energy and the negative gravitational energy both double, so the total energy remains zero. During the inflationary phase, the universe increases its size by a very large amount. Thus the total amount of energy available to make particles becomes very large. As Guth has remarked, "It is said that there's no such thing as a free lunch. But the universe is the ultimate free lunch."

The universe is not expanding in an inflationary way today. Thus there has to be some mechanism that would eliminate the very large effective cosmological constant and so change the rate of expansion from an accelerated one to one that is slowed down by gravity, as we have today. In the inflationary expansion one might expect that eventually the symmetry between the forces would be broken, just as super-cooled water always freezes in the end. The extra energy of the unbroken symmetry state would then be released and would reheat the universe to a temperature just below the critical temperature for symmetry between the forces. The universe would then go on to expand and cool just like the hot big bang model, but there would now be an explanation of why the universe was expanding at exactly the critical rate and why different regions had the same temperature.

In Guth's original proposal the phase transition was supposed to occur suddenly, rather like the appearance of ice crystals in very cold water. The idea was that "bubbles" of the new phase of broken symmetry would have formed in the old phase, like bubbles of steam surrounded by boiling water. The bubbles were supposed to expand and meet up with each other until the whole universe was in the new

phase. I ... transition was. I and several other people pointed out that the universe was expanding so fast that even if the bubbles grew at the speed of light, they would be moving away from each other and so could not join up. The universe would be left in a very nonuniform state, with some regions still having symmetry between the different forces. Such a model of the universe would not correspond to what we see.

In October 1981, I went to Moscow for a conference on quantum gravity. After the conference I gave a seminar on the inflationary model and its problems at the Sternberg Astronomical Institute. Before this, I had got someone else to give my lectures for me, because most people could not understand my voice. But there was not time to prepare this seminar, so I gave it myself, with one of my graduate students repeating my words. It worked well, and gave me much more contact with my audience. In the audience was a young Russian, Andrei Linde, from the Lebedev Institute in Moscow. He said that the difficulty with the bubbles not joining up could be avoided if the bubbles were so big that our region of the universe is all contained inside a single bubble. In order for this to work, the change from symmetry to broken symmetry must have taken place very slowly inside the bubble, but this is quite possible according to grand unified theories. Linde's idea of a slow breaking of symmetry was very good, but I later realized that his bubbles would have to have been bigger than the size of the universe at the time! I showed that instead the symmetry would have broken everywhere at the same time, rather than just inside bubbles. This would lead to a uniform universe, as we observe. I was very excited by this idea and discussed it with one of my students, Ian Moss. As a friend of Linde's, I was rather embarrassed, however, when I was later sent his paper by a scientific journal and asked whether it was suitable for publication. I replied that there was this flaw about the bubbles being bigger than the universe, but that the basic idea of a slow breaking of symmetry was very good. I recommended that the paper be published as it was because it would take Linde several months to

correct it, since anything he sent to the West would have to be passed by Soviet censorship, which was neither very skillful nor very quick with scientific papers. Instead, I wrote a short paper with Ian Moss in the same journal in which we pointed out this problem with the bubble and showed how it could be resolved.

The day after I got back from Moscow I set out for Philadelphia, where I was due to receive a medal from the Franklin Institute. My secretary, Judy Fella, had used her not inconsiderable charm to persuade British Airways to give herself and me free seats on a Concorde as a publicity venture. However, I was held up on my way to the airport by heavy rain and I missed the plane. Nevertheless, I got to Philadelphia in the end and received my medal. I was then asked to give a seminar on the inflationary universe at Drexel University in Philadelphia. I gave the same seminar about the problems of the inflationary universe, just as in Moscow.

A very similar idea to Linde's was put forth independently a few months later by Paul Steinhardt and Andreas Albrecht of the University of Pennsylvania. They are now given joint credit with Linde for what is called "the new inflationary model," based on the idea of a slow breaking of symmetry. (The old inflationary model was Guth's original suggestion of fast symmetry breaking with the formation of bubbles.)

The new inflationary model was a good attempt to explain why the universe is the way it is. However, I and several other people showed that, at least in its original form, it predicted much greater variations in the temperature of the microwave background radiation than are observed. Later work has also cast doubt on whether there could be a phase transition in the very early universe of the kind required. In my personal opinion, the new inflationary model is now dead as a scientific theory, although a lot of people do not seem to have heard of its demise and are still writing papers as if it were viable. A better model, called the chaotic inflationary model, was put forward by Linde in 1983. In this there is no phase transition or supercooling. Instead, there is a spin 0 field, which, because of quantum fluctuations, would have large

[illegible] nearest thing [illegible] space [illegible] be bent [illegible] over histories to Einstein's view of gravity [illegible] history of the whole universe. [illegible]

[illegible] quantum state of the universe.

[illegible] other hand, a third possibility arises. Because one is using Euclidean [illegible]

put forward for aesthetic or metaphysical reasons, but the real test is whether it makes predictions that agree with observation. This, however, is difficult to determine in the case of quantum gravity, for two reasons. First, as will be explained in Chapter 11, we are not yet sure exactly which theory successfully combines general relativity and quantum mechanics, though we know quite a lot about the form such a theory must have. Second, any model that described the whole universe in detail would be much too complicated mathematically for us to be able to calculate exact predictions. One therefore has to make simplifying assumptions and approximations—and even then, the problem of extracting predictions remains a formidable one.

Each history in the sum over histories will describe not only the space-time but everything in it as well, including any complicated organisms like human beings who can observe the history of the universe. This may provide another justification for the anthropic principle, for if all the histories are possible, then so long as we exist in one of the histories, we may use the anthropic principle to explain why the universe is found to be the way it is. Exactly what meaning can be attached to the other histories, in which we do not exist, is not clear. This view of a quantum theory of gravity would be much more satisfactory, however, if one could show that, using the sum over histories, our universe is not just one of the possible histories but one of the most probable ones. To do this, we must perform the sum over histories for all possible Euclidean space-times that have no boundary.

Under the "no boundary" proposal one learns that the chance of the universe being found to be following most of the possible histories is negligible, but there is a particular family of histories that are much more probable than the others. These histories may be pictured as being like the surface of the earth, with the distance from the North Pole representing imaginary time and the size of a circle of constant distance from the North Pole representing the spatial size of the universe. The universe starts at the North Pole as a single point. As one moves south, the circles of latitude at constant distance from the North

Pole get bigger, corresponding to the universe expanding with imaginary time (Fig. 8.1). The universe would reach a maximum size at the equator and would contract with increasing imaginary time to a single point at the South Pole. Even though the universe would have zero size at the North and South Poles, these points would not be singularities, any more than the North and South Poles on the earth are singular. The laws of science will hold at them, just as they do at the North and South Poles on the earth.

The history of the universe in real time, however, would look very different. At about ten or twenty thousand million years ago, it would have a minimum size, which was equal to the maximum radius of the history in imaginary time. At later real times, the universe would expand like the chaotic inflationary model proposed by Linde (but one would not now have to assume that the universe was created somehow in the right sort of state). The universe would expand to a very large size (Fig. 8.2) and eventually it would collapse again into what looks like a singularity in real time. Thus, in a sense, we are still all doomed, even if we keep away from black holes. Only if we could picture the universe in terms of imaginary time would there be no singularities.

If the universe really is in such a quantum state, there would be no singularities in the history of the universe in imaginary time. It might

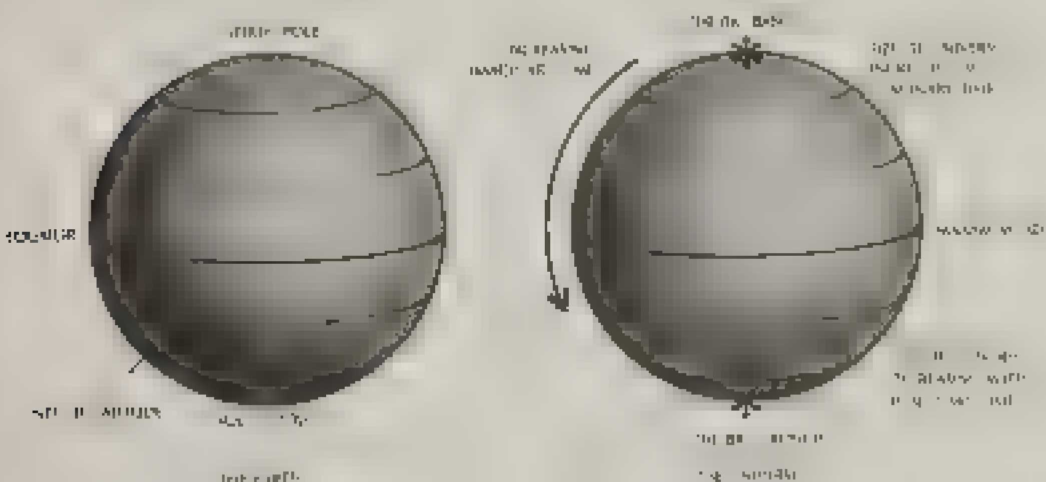

FIGURE 8.1

seem therefore that my more recent work had completely undone the results of my earlier work on singularities. But, as indicated above, the real importance of the singularity theorems was that they showed that the gravitational field must become so strong that quantum gravitational effects could not be ignored. This in turn led to the idea that the universe could be finite in imaginary time but without boundaries or singularities. When one goes back to the real time in which we live, however, there will still appear to be singularities. The poor astronaut who falls into a black hole will still come to a sticky end; only if he lived in imaginary time would he encounter no singularities.

This might suggest that the so-called imaginary time is really the real time, and that what we call real time is just a figment of our imaginations. In real time, the universe has a beginning and an end at singularities that form a boundary to space-time and at which the laws of science break down. But in imaginary time, there are no singularities or boundaries. So maybe what we call imaginary time is really more basic, and what we call real is just an idea that we invent to help us describe what we think the universe is like. But according to the approach I described in Chapter 1, a scientific theory is just a mathematical model we make to describe our observations: it exists only in our minds. So it is meaningless to ask: which is real, "real" or "imaginary" time? It is simply a matter of which is the more useful description.

One can also use the sum over histories, along with the no boundary proposal, to find which properties of the universe are likely to occur together. For example, one can calculate the probability that the universe is expanding at nearly the same rate in all different directions at a time when the density of the universe has its present value. In the simplified models that have been examined so far, this probability turns out to be high; that is, the proposed no boundary condition leads to the prediction that it is extremely probable that the present rate of expansion of the universe is almost the same in each direction. This is consistent with the observations of the microwave background radiation, which show that it has almost exactly the same intensity in any

[illegible]

be reduced by an additional red shift

[illegible]

affairs of the universe. With the success of scientific theories in describing events, most people have come to believe that God allows the universe to evolve according to a set of laws and does not intervene in the universe to break these laws. However, the laws do not tell us what the universe should have looked like when it started—it would still be up to God to wind up the clockwork and choose how to start it off. So long as the universe had a beginning, we could suppose it had a creator. But if the universe is really completely self-contained, having no boundary or edge, it would have neither beginning nor end: it would simply be. What place, then, for a creator?

CHAPTER 9

THE ARROW OF TIME

In previous chapters we have seen how our views of the nature of time have changed over the years. Up to the beginning of this century people believed in an absolute time. That is, each event could be labeled by a number called "time" in a unique way, and all good clocks would agree on the time interval between two events. However, the discovery that the speed of light appeared the same to every observer, no matter how he was moving, led to the theory of relativity—and in that one had to abandon the idea that there was a unique absolute time. Instead, each observer would have his own measure of time as recorded by a clock that he carried: clocks carried by different observers would not necessarily agree. Thus time became a more personal concept, relative to the observer who measured it.

When one tried to unify gravity with quantum mechanics, one had to introduce the idea of "imaginary" time. Imaginary time is indistinguishable from directions in space. If one can go north, one can turn around and head south; equally, if one can go forward in imaginary time, one ought to be able to turn round and go backward. This means

time there can be no important difference between the forward and backward directions of imaginary time. On the other hand, when one looks at "real" time, there's a very big difference between the forward and backward directions, as we all know. Where does this difference between the past and the future come from? Why do we remember the past but not the future?

The laws of science do not distinguish between the past and the future. More precisely, as explained earlier, the laws of science are unchanged under the combination of operations (or symmetries) known as C, P, and T. (C means changing particles for antiparticles. P means taking the mirror image, so left and right are interchanged. And T means reversing the direction of motion of all particles: in effect, running the motion backward.) The laws of science that govern the behavior of matter under all normal situations are unchanged under the combination of the two operations C and P on their own. In other words, life would be just the same for the inhabitants of another planet who were both mirror images of us and who were made of antimatter, rather than matter.

If the laws of science are unchanged by the combination of operations C and P, and also by the combination C, P, and T, they must also be unchanged under the operation T alone. Yet there is a big difference between the forward and backward directions of real time in ordinary life. Imagine a cup of water falling off a table and breaking into pieces on the floor. If you take a film of this, you can easily tell whether it is being run forward or backward. If you run it backward you will see the pieces suddenly gather themselves together off the floor and jump back to form a whole cup on the table. You can tell that the film is being run backward because this kind of behavior is never observed in ordinary life. If it were, crockery manufacturers would go out of business.

The explanation that is usually given as to why we don't see broken cups gathering themselves together off the floor and jumping back onto the table is that it is forbidden by the second law of thermo-

dynamics. This says that in any closed system disorder, or entropy, always increases with time. In other words, it is a form of Murphy's law: things always tend to go wrong! An intact cup on the table is a state of high order, but a broken cup on the floor is a disordered state. One can go readily from the cup on the table in the past to the broken cup on the floor in the future, but not the other way round.

The increase of disorder or entropy with time is one example of what is called an arrow of time, something that distinguishes the past from the future, giving a direction to time. There are at least three different arrows of time. First, there is the thermodynamic arrow of time, the direction of time in which disorder or entropy increases. Then, there is the psychological arrow of time. This is the direction in which we feel time passes, the direction in which we remember the past but not the future. Finally, there is the cosmological arrow of time. This is the direction of time in which the universe is expanding rather than contracting.

In this chapter I shall argue that the no boundary condition for the universe, together with the weak anthropic principle, can explain why all three arrows point in the same direction—and moreover, why a well-defined arrow of time should exist at all. I shall argue that the psychological arrow is determined by the thermodynamic arrow, and that these two arrows necessarily always point in the same direction. If one assumes the no boundary condition for the universe, we shall see that there must be well-defined thermodynamic and cosmological arrows of time, but they will not point in the same direction for the whole history of the universe. However, I shall argue that it is only when they do point in the same direction that conditions are suitable for the development of intelligent beings who can ask the question: why does disorder increase in the same direction of time as that in which the universe expands?

I shall discuss first the thermodynamic arrow of time. The second law of thermodynamics results from the fact that there are always many more disordered states than there are ordered ones. For example,

consider the pieces of a jigsaw in a box. There is one, and only one, arrangement in which the pieces make a complete picture. On the other hand, there are a very large number of arrangements in which the pieces are disordered and don't make a picture.

Suppose a system starts out in one of the small number of ordered states. As time goes by, the system will evolve according to the laws of science and its state will change. At a later time, it is more probable that the system will be in a disordered state than in an ordered one because there are more disordered states. Thus disorder will tend to increase with time if the system obeys an initial condition of high order.

Suppose the pieces of the jigsaw start off in a box in the ordered arrangement in which they form a picture. If you shake the box, the pieces will take up another arrangement. This will probably be a disordered arrangement in which the pieces don't form a proper picture, simply because there are so many more disordered arrangements. Some groups of pieces may still form parts of the picture, but the more you shake the box, the more likely it is that these groups will get broken up and the pieces will be in a completely jumbled state in which they don't form any sort of picture. So the disorder of the pieces will probably increase with time if the pieces obey the initial condition that they start off in a condition of high order.

Suppose, however, that God decided that the universe should finish up in a state of high order but that it didn't matter what state it started in. At early times the universe would probably be in a disordered state. This would mean that disorder would decrease with time. You would see broken cups gathering themselves together and jumping back onto the table. However, any human beings who were observing the cups would be living in a universe in which disorder decreased with time. I shall argue that such beings would have a psychological arrow of time that was backward. That is, they would remember events in the future, and not remember events in their past. When the cup was broken, they would remember it being on the table, but when it was on the table, they would not remember it being on the floor.

which disorder increases.

because we measure time in the direction in which disorder increases. You can't have a safer bet than that!

But why should the thermodynamic arrow of time exist at all? Or, in other words, why should the universe be in a state of high order at one end of time, the end that we call the past? Why is it not in a state of complete disorder at all times? After all, this might seem more probable. And why is the direction of time in which disorder increases the same as that in which the universe expands?

In the classical theory of general relativity one cannot predict how the universe would have begun because all the known laws of science would have broken down at the big bang singularity. The universe could have started out in a very smooth and ordered state. This would have led to well-defined thermodynamic and cosmological arrows of time, as we observe. But it could equally well have started out in a very lumpy and disordered state. In that case, the universe would already be in a state of complete disorder, so disorder could not increase with time. It would either stay constant, in which case there would be no well-defined thermodynamic arrow of time, or it would decrease, in which case the thermodynamic arrow of time would point in the opposite direction to the cosmological arrow. Neither of these possibilities agrees with what we observe. However, as we have seen, classical general relativity predicts its own downfall. When the curvature of space-time becomes large, quantum gravitational effects will become important and the classical theory will cease to be a good description of the universe. One has to use a quantum theory of gravity to understand how the universe began.

In a quantum theory of gravity, as we saw in the last chapter, in order to specify the state of the universe one would still have to say how the possible histories of the universe would behave at the boundary of space-time in the past. One could avoid this difficulty of having to describe what we do not and cannot know only if the histories satisfy the no boundary condition: they are finite in extent but have no boundaries, edges, or singularities. In that case, the beginning of time

the thermodynamic arrow of time

the universe contracted

[illegible] recontract, or inside black holes.

[illegible]

[illegible] one believes that the universe will expand and then contract again, [illegible] phase.

[illegible]

thermodynamic arrow of time

your brain will have increased by about two million units. However, while you have been reading the book, you will have converted at least a thousand calories of ordered energy, in the form of food, into disordered energy, in the form of heat that you lose to the air around you by convection and sweat. This will increase the disorder of the universe by about twenty million million million million units – or about ten million million million times the increase in order in your brain – and that's if you remember *everything* in this book. In the next chapter but one I will try to increase the order in our neck of the woods a little further by explaining how people are trying to fit together the partial theories I have described to form a complete unified theory that would cover everything in the universe.

CHAPTER 10

WORMHOLES AND TIME TRAVEL

The last chapter discussed why we see time go forward: why disorder increases and why we remember the past but not the future. Time was treated as if it were a straight railway line on which one could only go one way or the other.

But what if the railway line had loops and branches so that a train could keep going forward but come back to a station it had already passed? In other words, might it be possible for someone to travel into the future or the past?

H. G. Wells in *The Time Machine* explored these possibilities as have countless other writers of science fiction. Yet many of the ideas of science fiction, like submarines and travel to the moon, have become matters of science fact. So what are the prospects for time travel?

The first indication that the laws of physics might really allow people to travel in time came in 1949 when Kurt Gödel discovered a new space-time allowed by general relativity. Gödel was a mathematician who was famous for proving that it is impossible to prove all true

statements, even if you devote yourself to trying to prove all the true statements in a subject as apparently clear and elementary as arithmetic. Like the uncertainty principle, Gödel's incompleteness theorem may be a fundamental limitation on our ability to understand and predict the universe, but so far at least it hasn't seemed to be an obstacle in our search for a complete unified theory.

Gödel got to know about general relativity when he and Einstein spent their later years at the Institute for Advanced Study in Princeton. His spacetime had the curious property that the whole universe was rotating. One might ask: "Rotating with respect to what?" The answer is that distant matter would be rotating with respect to directions that little tops or gyroscopes point in.

This had the side effect that it would be possible for someone to go off in a rocket ship and return to earth before he set out. This property really upset Einstein, who had thought that general relativity wouldn't allow time travel. However, given Einstein's record of ill-founded opposition to gravitational collapse and the uncertainty principle, maybe this was an encouraging sign. The solution Gödel found doesn't correspond to the universe we live in because we can show that the universe is not rotating. It also had a non-zero value of the cosmological constant that Einstein introduced when he thought the universe was unchanging. After Hubble discovered the expansion of the universe, there was no need for a cosmological constant and it is now generally believed to be zero. However, other more reasonable space-times that are allowed by general relativity and which permit travel into the past have since been found. One is in the interior of a rotating black hole. Another is a space-time that contains two cosmic strings moving past each other at high speed. As their name suggests, cosmic strings are objects that are like string in that they have length but a tiny cross section. Actually, they are more like rubber bands because they are under enormous tension, something like a million million million million tons. A cosmic string attached to the earth could accelerate it from 0 to 60 mph in 1/30th of a second. Cosmic

[illegible]

The [illegible]
[illegible]
space-time sufficiently to allow it?

[illegible] to rela-
tivity, nothing can travel faster than light. If we therefore sent a
[illegible]
tioned in Chapter 2.

[illegible]

science fiction writers has been to suppose that we would one day discover how to travel faster than light. What most of these authors don't seem to have realized is that if you can travel faster than light, the theory of relativity implies you can also travel back in time, as the following limerick says.

There was a young lady of Wight
Who travelled much faster than light.
She departed one day,
In a relative way,
And arrived on the previous night.

The point is that the theory of relativity says that there is no unique measure of time that all observers will agree on. Rather, each observer has his or her own measure of time. If it is possible for a rocket traveling below the speed of light to get from event A (say, the final of the 100-meter race of the Olympic Games in 2012) to event B (say, the opening of the 100,004th meeting of the Congress of Alpha Centauri), then all observers will agree that event A happened before event B according to their times. Suppose, however, that the spaceship would have to travel faster than light to carry the news of the race to the Congress. Then observers moving at different speeds can disagree about whether event A occurred before B or vice versa. According to the time of an observer who is at rest with respect to the earth, it may be that the Congress opened after the race. Thus this observer would think that a spaceship could get from A to B in time if only it could ignore the speed-of-light speed limit. However, to an observer at Alpha Centauri moving away from the earth at nearly the speed of light, it would appear that event B, the opening of the Congress, would occur before event A, the 100-meter race. The theory of relativity says that the laws of physics appear the same to observers moving at different speeds.

This has been well tested by experiment and is likely to remain a feature even if we find a more advanced theory to replace relativity.

[illegible] one could even get back before the [illegible] and place a bet on it in the sure knowledge that one would win.

[illegible]

[illegible]

[illegible]

[illegible] respectable source.

[illegible] matter with negative energy density.

[illegible]

[illegible] This means that [illegible] photons [illegible] between the plates [illegible] and the waves will cancel out.

Because [illegible] photons between the plates [illegible] effects.

The [illegible] plates [illegible]

[illegible] time travel [illegible]

but unless human nature changes radically, it is difficult to believe that some visitor from the future would not spill the beans. Of course, some people would claim that sightings of UFOs are evidence that we are being visited either by aliens or by people from the future. (If the aliens were to get here in reasonable time, they would need faster-than-light travel, so the two possibilities may be equivalent.)

However, I think that any visit by aliens or people from the future would be much more obvious and, probably, much more unpleasant. If they are going to reveal themselves at all, why do so only to those who are not regarded as reliable witnesses? If they are trying to warn us of some great danger, they are not being very effective.

A possible way to explain the absence of visitors from the future would be to say that the past is fixed because we have observed it and seen that it does not have the kind of warping needed to allow travel back from the future. On the other hand, the future is unknown and open, so it might well have the curvature required. This would mean that any time travel would be confined to the future. There would be no chance of Captain Kirk and the Starship *Enterprise* turning up at the present time.

This might explain why we have not yet been overrun by tourists from the future, but it would not avoid the problems that would arise if one were able to go back and change history. Suppose, for example, you went back and killed your great-great-grandfather while he was still a baby. There are many versions of this paradox but they are essentially equivalent: one would get contradictions if one were free to change the past.

There seem to be two possible resolutions to the paradoxes posed by time travel. One I shall call the consistent histories approach. It says that even if space-time is warped so that it would be possible to travel into the past, what happens in space-time must be a consistent solution of the laws of physics. According to this viewpoint, you could not go back in time unless history showed that you had already arrived in the past and, while there, had not killed your great-great-grandfather or

would have no free will.

satisfactory history.

The Feynman sum over histories does allow travel into the past on a microscopic scale. In Chapter 5 we saw that the laws of science are unchanged by combinations of the operations C, P, and T. This means that an antiparticle spinning in the anticlockwise direction and moving from A to B can also be viewed as an ordinary particle spinning clockwise and moving backward in time from B to A. Similarly, an ordinary particle moving forward in time is equivalent to an antiparticle moving backward in time. As has been discussed in this chapter and Chapter 7, "empty" space is filled with pairs of virtual particles and antiparticles that appear together, move apart, and then come back together and annihilate each other.

So, one can regard the pair of particles as a single particle moving on a closed loop in space-time. When the pair is moving forward in time (from the event at which it appears to that at which it annihilates), it is called a particle. But when the particle is traveling back in time (from the event at which the pair annihilates to that at which it appears), it is said to be an antiparticle traveling forward in time.

The explanation of how black holes can emit particles and radiation (given in Chapter 7) was that one member of a virtual particle/antiparticle pair (say, the antiparticle) might fall into the black hole, leaving the other member without a partner with which to annihilate. The forsaken particle might fall into the hole as well, but it might also escape from the vicinity of the black hole. If so, to an observer at a distance it would appear to be a particle emitted by the black hole.

One can, however, have a different but equivalent intuitive picture of the mechanism for emission from black holes. One can regard the member of the virtual pair that fell into the black hole (say, the antiparticle) as a particle traveling backward in time out of the hole. When it gets to the point at which the virtual particle/antiparticle pair appeared together, it is scattered by the gravitational field into a particle traveling forward in time and escaping from the black hole. If, instead, it were the particle member of the virtual pair that fell into the hole, one could regard it as an antiparticle traveling back in time and coming

[illegible]

are reasons to believe it is true

[illegible]

knowing the future

CHAPTER 11

THE UNIFICATION OF PHYSICS

As was explained in the first chapter, it would be very difficult to construct a complete unified theory of everything in the universe all at one go. So instead we have made progress by finding partial theories that describe a limited range of happenings and by neglecting other effects or approximating them by certain numbers. (Chemistry, for example, allows us to calculate the interactions of atoms, without knowing the internal structure of an atom's nucleus.) Ultimately, however, one would hope to find a complete, consistent, unified theory that would include all these partial theories as approximations, and that did not need to be adjusted to fit the facts by picking the values of certain arbitrary numbers in the theory. The quest for such a theory is known as "the unification of physics." Einstein spent most of his later years unsuccessfully searching for a unified theory, but the time was not ripe: there were partial theories for gravity and the electromagnetic force, but very little was known about the nuclear forces. Moreover, Einstein refused to believe in the reality of quantum mechanics, despite the important role he had played in its development. Yet it seems that

[illegible] porate this principle.

[illegible]

[illegible]

small size.

have to be chosen to fit the observations.

dimensions) and that in a sense all these particles could be regarded as different aspects of the same "superparticle," thus unifying the matter particles with spin ½ and 3/2 with the force-carrying particles of spin 0, 1, and 2. The virtual particle/antiparticle pairs of spin ½ and 3/2 would have negative energy, and so would tend to cancel out the positive energy of the spin 2, 1, and 0 virtual pairs. This would cause many of the possible infinities to cancel out, but it was suspected that some infinities might still remain. However, the calculations required to find out whether or not there were any infinities left uncanceled were so long and difficult that no one was prepared to undertake them. Even with a computer it was reckoned it would take at least four years, and the chances were very high that one would make at least one mistake, probably more. So one would know one had the right answer only if someone else repeated the calculation and got the same answer, and that did not seem very likely.

Despite these problems, and the fact that the particles in the supergravity theories did not seem to match the observed particles, most scientists believed that supergravity was probably the right answer to the problem of the unification of physics. It seemed the best way of unifying gravity with the other forces. However, in 1984 there was a remarkable change of opinion in favor of what are called string theories. In these theories the basic objects are not particles, which occupy a single point of space, but things that have a length but no other dimension, like an infinitely thin piece of string. These strings may have ends (the so-called open strings) or they may be joined up with themselves in closed loops (closed strings) (Fig. 10.1 and Fig. 10.2). A particle occupies one point of space at each instant of time. Thus its history can be represented by a line in space-time (the "world-line"). A string, on the other hand, occupies a line in space at each moment of time. So its history in space-time is a two-dimensional surface called the world-sheet. (Any point on such a world-sheet can be described by two numbers, one specifying the time and the other the position of the point on the string.) The world-sheet of an open string is a strip; its

edges represent the paths through space-time of the ends of the string (Fig. 11.1). The world-sheet of a closed string is a cylinder or tube (Fig. 11.2); a slice through the tube is a circle, which represents the position of the string at one particular time.

Two pieces of string can join together to form a single string; in the case of open strings they simply join at the ends (Fig. 11.3), while in the case of closed strings it is like the two legs joining on a pair of trousers (Fig. 11.4). Similarly, a single piece of string can divide into two strings. In string theories, what were previously thought of as particles are now pictured as waves traveling down the string, like waves on a vibrating kite string. The emission or absorption of one particle by another corresponds to the dividing or joining together of strings. For example, the gravitational force of the sun on the earth was pictured in particle

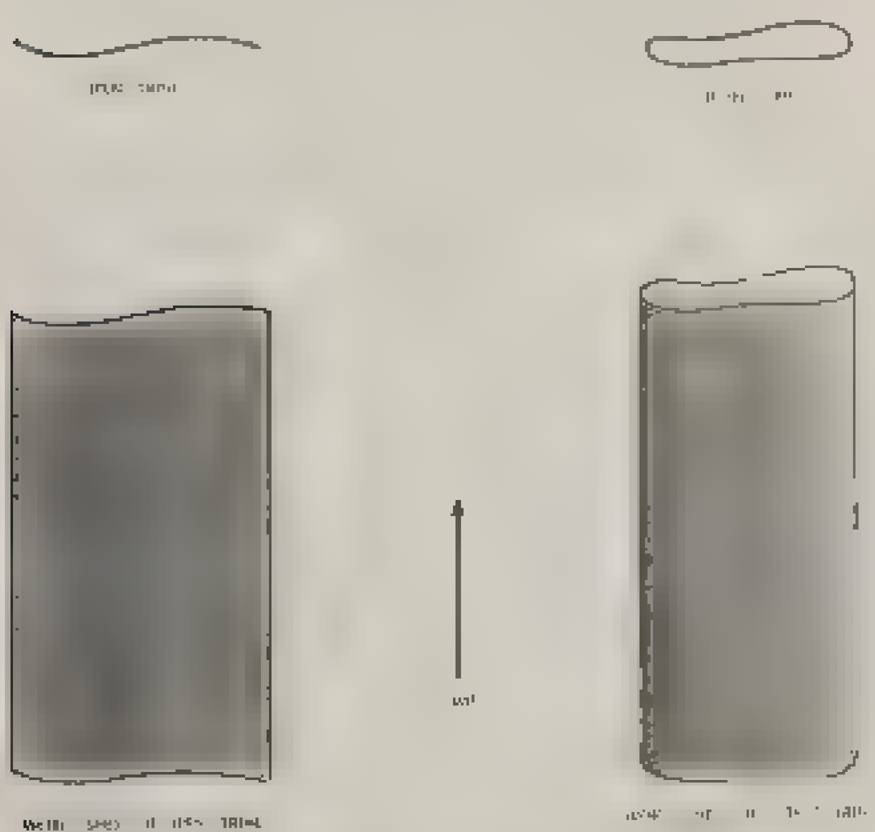

FIGURE 11.1 AND FIGURE 11.2

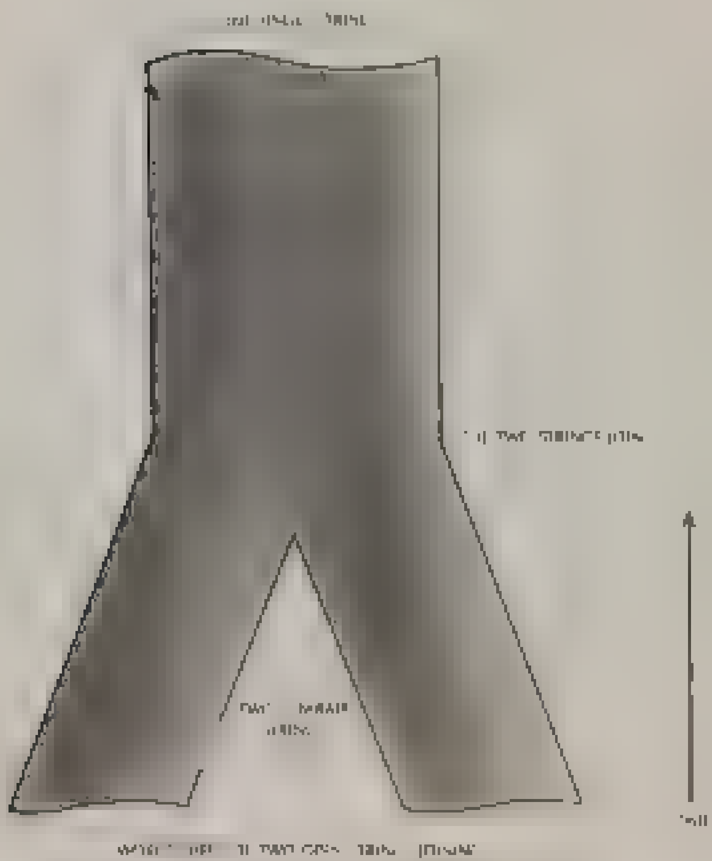

FIGURE 11.4

forces as being caused by the emission of a graviton by a particle in the sun and its absorption by a particle in the earth (Fig. 11.5). In string theory, this process corresponds to an H-shaped tube or pipe (Fig. 11.6) (string theory is rather like plumbing, in a way). The two vertical sides of the H correspond to the particles in the sun and the earth, and the horizontal crossbar corresponds to the graviton that travels between them.

String theory has a curious history. It was originally invented in the late 1960s in an attempt to find a theory to describe the strong force. The idea was that particles like the proton and the neutron could be regarded as waves on a string. The strong forces between the particles would correspond to pieces of string that went between other bits of string, as in a spider's web. For this theory to give the observed value of

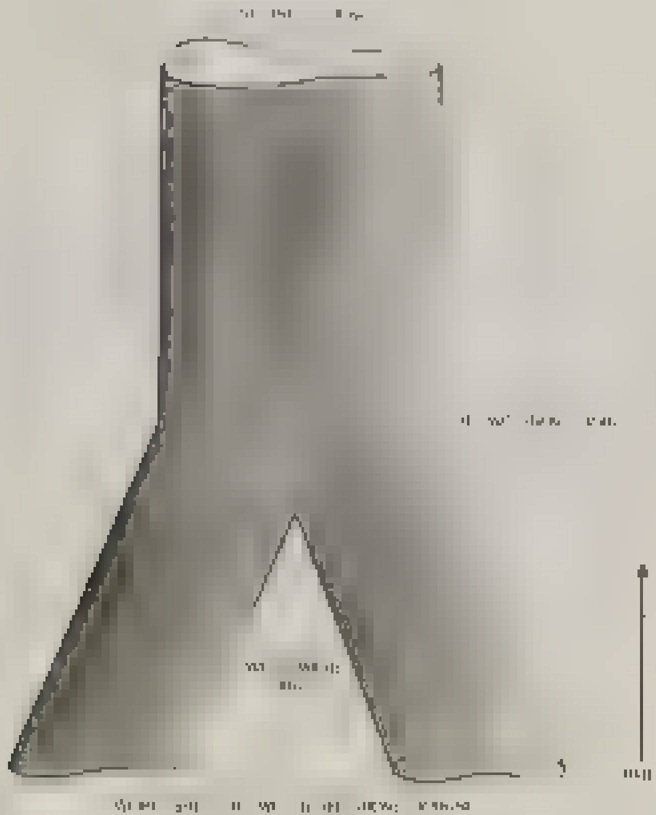

FIGURE 11.4

the strong force between particles, the strings had to be like rubber bands with a pull of about ten tons.

In 1974 Joël Scherk from Paris and John Schwarz from the California Institute of Technology published a paper in which they showed that string theory could describe the gravitational force, but only if the tension in the string were very much higher, about a thousand million million million million million million tons (1 with thirty-nine zeros after it). The predictions of the string theory would be just the same as those of general relativity on normal length scales, but they would differ at very small distances, less than a thousand million million million million millionth of a centimeter (a centimeter divided by 1 with thirty-three zeros after it). Their work did not receive much attention, however, because at just about that time most people abandoned the original string theory of the strong force in favor of the

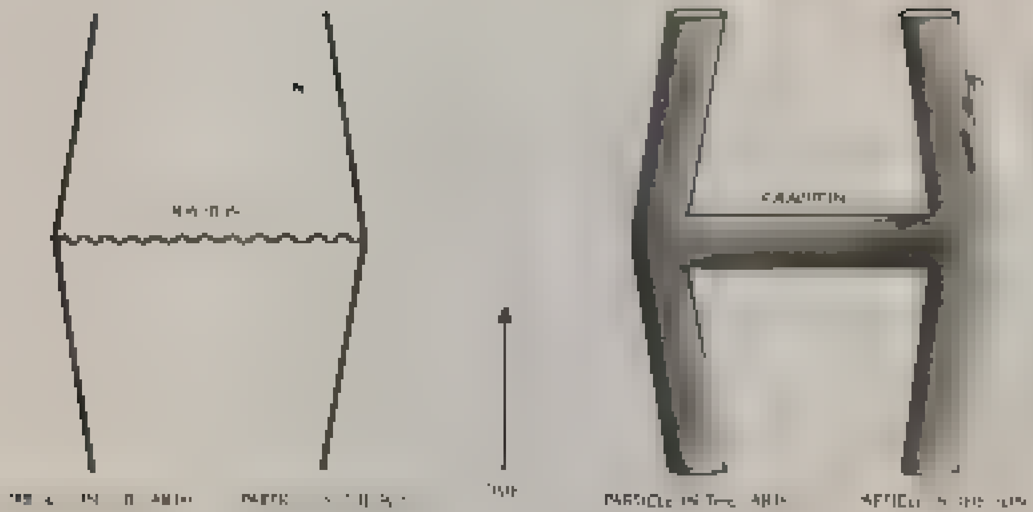

FIGURE 11.5 AND FIGURE 11.6

theory based on quarks and gluons, which seemed to fit much better with observations. Scherk died in tragic circumstances (he suffered from diabetes and went into a coma when no one was around to give him an injection of insulin). So Schwarz was left alone as almost the only supporter of string theory, but now with the much higher proposed value of the string tension.

In 1984 interest in strings suddenly revived, apparently for two reasons. One was that people were not really making much progress toward showing that supergravity was finite or that it could explain the kinds of particles that we observe. The other was the publication of a paper by John Schwarz and Mike Green of Queen Mary College, London, that showed that string theory might be able to explain the existence of particles that have a built-in left-handedness, like some of the particles that we observe. Whatever the reasons, a large number of people soon began to work on string theory and a new version was developed, the so-called heterotic string, which seemed as if it might be able to explain the types of particles that we observe.

String theories also lead to infinities, but it is thought they will all cancel out in versions like the heterotic string (though this is not yet known for certain). String theories, however, have a bigger problem:

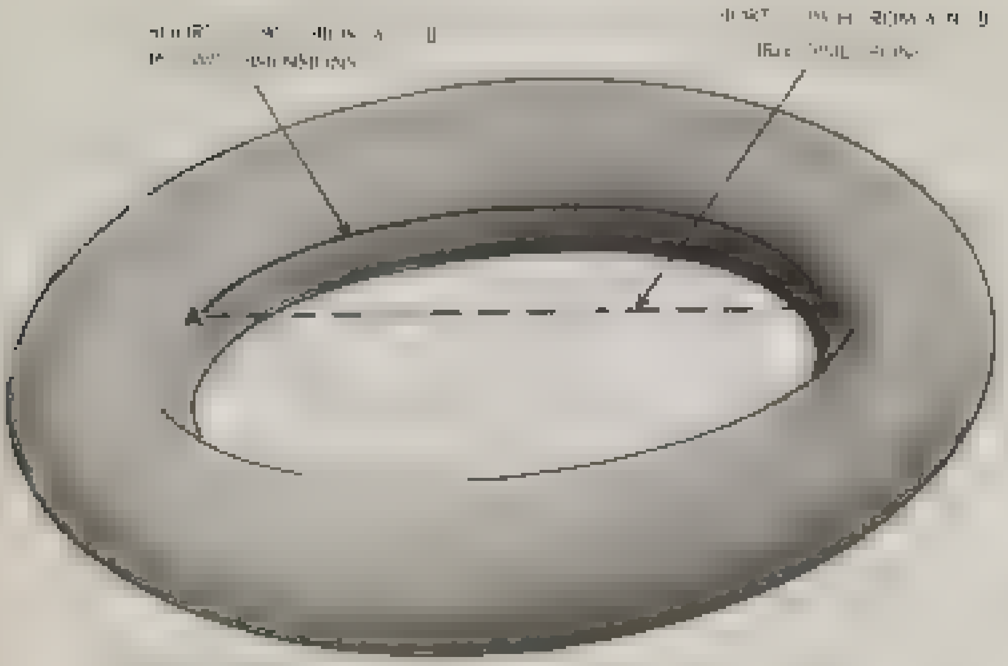

FIGURE 11.7

theory seems to be consistent only if space-time has either ten or twenty-six dimensions, instead of the usual four! Of course, extra space-time dimensions are a commonplace of science fiction; indeed, they provide an ideal way of overcoming the normal restriction of general relativity that one cannot travel faster than light or back in time (see Chapter 10). The idea is to take a shortcut through the extra dimensions. One can picture this in the following way. Imagine that the space we live in has only two dimensions and is curved like the surface of an anchor ring or torus (Fig. 11.7). If you were on one side of the inside edge of the ring and you wanted to get to a point on the other side, you would have to go round the inner edge of the ring. However, if you were able to travel in the third dimension, you could cut straight across.

Why don't we notice all these extra dimensions, if they are really there? Why do we see only three space dimensions and one time dimension? The suggestion is that the other dimensions are curved up into a space of very small size, something like a million million million million millionth of an inch. This is so small that we just don't notice it

dimensions remain tightly curled up?

blood in a two-dimensional creature.

TWO-DIMENSIONAL ANIMAL

FIGURE 11.8

and so on. The significance of this is that the orbits of planets, like the earth, around the sun would be unstable: the least disturbance from a circular orbit (such as would be caused by the gravitational attraction of other planets) would result in the earth spiraling away from or into the sun. We would either freeze or be burned up. In fact, the same behavior of gravity with distance in more than three space dimensions means that the sun would not be able to exist in a stable state with pressure balancing gravity. It would either fall apart or it would collapse to form a black hole. In either case, it would not be of much use as a source of heat and light for life on earth. On a smaller scale, the electrical forces that cause the electrons to orbit round the nucleus in an atom would behave in the same way as gravitational forces. Thus the electrons would either escape from the atom altogether or would spiral into the nucleus. In either case, one could not have atoms as we know them.

It seems clear then that life, at least as we know it, can exist only in regions of space-time in which one time and three space dimensions are not curled up small. This would mean that one could appeal to the weak anthropic principle, provided one could show that string theory does at least allow there to be such regions of the universe—and it seems that indeed string theory does. There may well be other regions of the universe, or other universes (whatever that may mean), in which all the dimensions are curled up small or in which more than four dimensions are nearly flat, but there would be no intelligent beings in such regions to observe the different number of effective dimensions.

Another problem is that there are at least four different string theories (open strings and three different closed string theories) and millions of ways in which the extra dimensions predicted by string theory could be curled up. Why should just one string theory and one kind of curling up be picked out? For a time there seemed no answer, and progress got bogged down. Then, from about 1994, people started discovering what are called dualities: different string theories and different ways of curling up the extra dimensions could lead to the same results in four dimensions. Moreover, as well as particles, which occupy a single point of space, and strings, which are lines, there were found to be other objects called p-branes, which occupied two-dimensional or higher-dimensional volumes in space. (A particle can be regarded as a 0-brane and a string as a 1-brane but there were also p-branes for p=2 to p=9.) What this seems to indicate is that there is a sort of democracy among supergravity, string, and p-brane theories: they seem to fit together but none can be said to be more fundamental than the others. They appear to be different approximations to some fundamental theory that are valid in different situations.

People have searched for this underlying theory, but without any success so far. However, I believe there may not be any single formulation of the fundamental theory any more than, as Gödel showed, one could formulate arithmetic in terms of a single set of axioms. Instead it

may be like maps—you can't use a single map to describe the surface of the earth or an anchor ring: you need at least two maps in the case of the earth and four for the anchor ring to cover every point. Each map is valid only in a limited region, but different maps will have a region of overlap. The collection of maps provides a complete description of the surface. Similarly, in physics it may be necessary to use different formulations in different situations, but two different formulations would agree in situations where they can both be applied. The whole collection of different formulations could be regarded as a complete unified theory, though one that could not be expressed in terms of a single set of postulates.

But can there really be such a unified theory? Or are we perhaps just chasing a mirage? There seem to be three possibilities:

1. There really is a complete unified theory (or a collection of overlapping formulations), which we will someday discover if we are smart enough.
2. There is no ultimate theory of the universe, just an infinite sequence of theories that describe the universe more and more accurately.
3. There is no theory of the universe: events cannot be predicted beyond a certain extent but occur in a random and arbitrary manner.

Some would argue for the third possibility on the grounds that if there were a complete set of laws, that would infringe God's freedom to change his mind and intervene in the world. It's a bit like the old paradox: can God make a stone so heavy that he can't lift it? But the idea that God might want to change his mind is an example of the fallacy, pointed out by St. Augustine, of imagining God as a being existing in time: time is a property only of the universe that God created. Presumably, he knew what he intended when he set it up!

With the advent of quantum mechanics, we have come to recognize

that events cannot be predicted with complete accuracy but that there is always a degree of uncertainty. If one likes, one could ascribe this randomness to the intervention of God, but it would be a very strange kind of intervention: there is no evidence that it is directed toward any purpose. Indeed, if it were, it would by definition not be random. In modern times, we have effectively removed the third possibility above by redefining the goal of science: our aim is to formulate a set of laws that enables us to predict events only up to the limit set by the uncertainty principle.

The second possibility, that there is an infinite sequence of more and more refined theories, is in agreement with all our experience so far. On many occasions we have increased the sensitivity of our measurements or made a new class of observations, only to discover new phenomena that were not predicted by the existing theory, and to account for these we have had to develop a more advanced theory. It would therefore not be very surprising if the present generation of grand unified theories was wrong in claiming that nothing essentially new will happen between the electroweak unification energy of about 100 GeV and the grand unification energy of about a thousand million million GeV. We might indeed expect to find several new layers of structure more basic than the quarks and electrons that we now regard as "elementary" particles.

However, it seems that gravity may provide a limit to this sequence of "boxes within boxes." If one had a particle with an energy above what is called the Planck energy, ten million million million GeV (1 followed by nineteen zeros), its mass would be so concentrated that it would cut itself off from the rest of the universe and form a little black hole. Thus it does seem that the sequence of more and more refined theories should have some limit as we go to higher and higher energies, so that there should be some ultimate theory of the universe. Of course, the Planck energy is a very long way from the energies of around a hundred GeV, which are the most that we can produce in the laboratory at the present time. We shall not bridge that gap with particle

[illegible]

theory of relativity. Now [illegible]

a great achievement, at least in outline. We would then of course have some understanding of the laws that govern the universe and are responsible for our existence.

Even if we do discover a complete unified theory, it would not mean that we would be able to predict events in general, for two reasons. The first is the limitation that the uncertainty principle of quantum mechanics sets on our powers of prediction. There is nothing we can do to get around that. In practice, however, this first limitation is less restrictive than the second one. It arises from the fact that we could not solve the equations of the theory exactly, except in very simple situations. (We cannot even solve exactly for the motion of three bodies in Newton's theory of gravity, and the difficulty increases with the number of bodies and the complexity of the theory.) We already know the laws that govern the behavior of matter under all but the most extreme conditions. In particular, we know the basic laws that underlie all of chemistry and biology. Yet we have certainly not reduced these subjects to the status of solved problems: we have, as yet, had little success in predicting human behavior from mathematical equations! So even if we do find a complete set of basic laws, there will still be in the years ahead the intellectually challenging task of developing better approximation methods, so that we can make useful predictions of the probable outcomes in complicated and realistic situations. A complete, consistent, unified theory is only the first step: our goal is a complete *understanding* of the events around us, and of our own existence.

CHAPTER 12

CONCLUSION

We find ourselves in a bewildering world. We want to make sense of what we see around us and to ask: What is the nature of the universe? What is our place in it and where did it and we come from? Why is it the way it is?

To try to answer these questions we adopt some "world picture." Just as an infinite tower of tortoises supporting the flat earth is such a picture, so is the theory of superstrings. Both are theories of the universe, though the latter is much more mathematical and precise than the former. Both theories lack observational evidence: no one has ever seen a giant tortoise with the earth on its back, but then, no one has seen a superstring either. However, the tortoise theory fails to be a good scientific theory because it predicts that people should be able to fall off the edge of the world. This has not been found to agree with experience, unless that turns out to be the explanation for the people who are supposed to have disappeared in the Bermuda Triangle!

The earliest theoretical attempts to describe and explain the universe involved the idea that events and natural phenomena were controlled by

by spirits with human emotions who acted in a very humanlike and unpredictable manner. These spirits inhabited natural objects, like rivers and mountains, including celestial bodies, like the sun and moon. They had to be placated and their favor sought in order to ensure the fertility of the soil and the rotation of the seasons. Gradually, however, it must have been noticed that there were certain regularities: the sun always rose in the east and set in the west, whether or not a sacrifice had been made to the sun god. Further, the sun, the moon, and the planets followed precise paths across the sky that could be predicted in advance with considerable accuracy. The sun and the moon might still be gods, but they were gods who obeyed strict laws, apparently without any exceptions, if one discounts stories like that of the sun stopping for Joshua.

At first, these regularities and laws were obvious only in astronomy and a few other situations. However, as civilization developed, and particularly in the last 300 years, more and more regularities and laws were discovered. The success of these laws led Laplace at the beginning of the nineteenth century to postulate scientific determinism, that is, he suggested that there would be a set of laws that would determine the evolution of the universe precisely, given its configuration at one time.

Laplace's determinism was incomplete in two ways. It did not say how the laws should be chosen and it did not specify the initial configuration of the universe. These were left to God. God would choose how the universe began and what laws it obeyed, but he would not intervene in the universe once it had started. In effect, God was confined to the areas that nineteenth-century science did not understand.

We now know that Laplace's hopes of determinism cannot be realized, at least in the terms he had in mind. The uncertainty principle of quantum mechanics implies that certain pairs of quantities, such as the position and velocity of a particle, cannot both be predicted with complete accuracy. Quantum mechanics deals with this situation via a class of quantum theories in which particles don't have well-defined

[illegible] unpredictability.

[illegible] pened and how the universe began.

[illegible]

and time together might form a finite, four-dimensional space without singularities or boundaries, like the surface of the earth but with more dimensions. It seemed that this idea could explain many of the observed features of the universe, such as its large-scale uniformity and also the smaller-scale departures from homogeneity, like galaxies, stars, and even human beings. It could even account for the arrow of time that we observe. But if the universe is completely self-contained, with no singularities or boundaries, and completely described by a unified theory, that has profound implications for the role of God as Creator.

Einstein once asked the question: "How much choice did God have in constructing the universe?" If the no boundary proposal is correct, he had no freedom at all to choose initial conditions. He would, of course, still have had the freedom to choose the laws that the universe obeyed. This, however, may not really have been all that much of a choice; there may well be only one, or a small number, of complete unified theories, such as the heterotic string theory, that are self-consistent and allow the existence of structures as complicated as human beings who can investigate the laws of the universe and ask about the nature of God.

Even if there is only one possible unified theory, it is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe? The usual approach of science of constructing a mathematical model cannot answer the questions of why there should be a universe for the model to describe. Why does the universe go to all the bother of existing? Is the unified theory so compelling that it brings about its own existence? Or does it need a creator, and, if so, does he have any other effect on the universe? And who created him?

Up to now, most scientists have been too occupied with the development of new theories that describe *what* the universe is to ask the question *why*. On the other hand, the people whose business it is to ask *why*, the philosophers, have not been able to keep up with the advance of scientific theories. In the eighteenth century, philosophers considered

ered the whole of human knowledge, including science, to be their field and discussed questions such as: did the universe have a beginning? However, in the nineteenth and twentieth centuries, science became too technical and mathematical for the philosophers, or anyone else except a few specialists. Philosophers reduced the scope of their inquiries so much that Wittgenstein, the most famous philosopher of this century, said, "The sole remaining task for philosophy is the analysis of language." What a comedown from the great tradition of philosophy from Aristotle to Kant!

However, if we do discover a complete theory, it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all, philosophers, scientists, and just ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason – for then we would know the mind of God.

ALBERT EINSTEIN

Einstein's connection with the politics of the nuclear bomb is well known: he signed the famous letter to President Franklin Roosevelt that persuaded the United States to take the idea seriously, and he engaged in postwar efforts to prevent nuclear war. But these were not just the isolated actions of a scientist dragged into the world of politics. Einstein's life was, in fact, to use his own words, "divided between politics and equations."

Einstein's earliest political activity came during the First World War, when he was a professor in Berlin. Sickened by what he saw as the waste of human lives, he became involved in antiwar demonstrations. His advocacy of civil disobedience and public encouragement of people to refuse conscription did little to endear him to his colleagues. Then, following the war, he directed his efforts toward reconciliation and improving international relations. This too did not make him popular, and soon his politics were making it difficult for him to visit the United States, even to give lectures.

Einstein's second great cause was Zionism. Although he was Jewish

[illegible] control of nuclear weaponry.

[illegible] something for eternity.[illegible]

GALILEO GALILEI

Galileo, perhaps more than any other single person, was responsible for the birth of modern science. His renowned conflict with the Catholic Church was central to his philosophy, for Galileo was one of the first to argue that man could hope to understand how the world works, and, moreover, that we could do this by observing the real world.

Galileo had believed Copernican theory (that the planets orbited the sun) since early on, but it was only when he found the evidence needed to support the idea that he started to publicly support it. He wrote about Copernicus's theory in Italian (not the usual academic Latin), and soon his views became widely supported outside the universities. This annoyed the Aristotelian professors, who united against him seeking to persuade the Catholic Church to ban Copernicanism.

Galileo, worried by this, traveled to Rome to speak to the ecclesiastical authorities. He argued that the Bible was not intended to tell us anything about scientific theories, and that it was usual to assume that, where the Bible conflicted with common sense, it was being allegorical.

[illegible]

[illegible] tions on God's omnipotence.

The book [illegible]

[illegible] Galileo acquiesc[illegible]

[illegible]

ISAAC NEWTON

Isaac Newton was not a pleasant man. His relations with other academics were notorious, with most of his later life spent embroiled in heated disputes. Following publication of *Principia Mathematica*—surely the most influential book ever written in physics—Newton had risen rapidly into public prominence. He was appointed president of the Royal Society and became the first scientist ever to be knighted.

Newton soon clashed with the Astronomer Royal, John Flamsteed, who had earlier provided Newton with much-needed data for *Principia*, but was now withholding information that Newton wanted. Newton would not take no for an answer; he had himself appointed to the governing body of the Royal Observatory and then tried to force immediate publication of the data. Eventually he arranged for Flamsteed's work to be seized and prepared for publication by Flamsteed's mortal enemy, Edmond Halley. But Flamsteed took the case to court and, in the nick of time, won a court order preventing distribution of the stolen work. Newton was incensed and sought his

editions of *Principia*

GLOSSARY

Absolute zero: The lowest possible temperature, at which substances contain no heat energy.

Acceleration: The rate at which the speed of an object is changing.

Anthropic principle: We see the universe the way it is because if it were different we would not be here to observe it.

Antiparticle: Each type of matter particle has a corresponding antiparticle. When a particle collides with its antiparticle, they annihilate, leaving only energy.

Atom: The basic unit of ordinary matter, made up of a tiny nucleus (consisting of protons and neutrons) surrounded by orbiting electrons.

Big bang: The singularity at the beginning of the universe.

Big crunch: The singularity at the end of the universe.

Black hole: A region of space-time from which nothing, not even light, can escape, because gravity is so strong.

Casimir effect: The attractive pressure between two flat, parallel metal plates placed very near to each other in a vacuum. The pressure is due to a reduction in the usual number of virtual particles in the space between the plates.

Chandrasekhar limit: The maximum possible mass of a stable cold star, above which it must collapse into a black hole.

Conservation of energy: The law of science that states that energy (or its equivalent in mass) can neither be created nor destroyed.

Coordinates: Numbers that specify the position of a point in space and time.

Cosmological constant: A mathematical device used by Einstein to give space-time an inbuilt tendency to expand.

Cosmology: The study of the universe as a whole.

Dark matter: Matter in galaxies, clusters, and possibly between clusters, that can not be observed directly but can be detected by its gravitational effect. As much as 90 percent of the mass of the universe may be in the form of dark matter.

Duality: A correspondence between apparently different theories that lead to the same physical results.

Einstein-Rosen bridge: A thin tube of space-time linking two black holes. *Also see* **Wormhole**.

Electric charge: A property of a particle by which it may repel (or attract) other particles that have a charge of similar (or opposite) sign.

Electromagnetic force: The force that arises between particles with electric charge; the second strongest of the four fundamental forces.

Electron: A particle with negative electric charge that orbits the nucleus of an atom.

Electroweak unification energy: The energy (around 100 GeV) above which the distinction between the electromagnetic force and the weak force disappears.

Elementary particle: A particle that, it is believed, cannot be subdivided.

Event: A point in space-time, specified by its time and place.

Event horizon: The boundary of a black hole.

Exclusion principle: The idea that two identical spin-1/2 particles cannot have (within the limits set by the uncertainty principle) both the same position and the same velocity.

Field: Something that exists throughout space and time, as opposed to a particle that exists at only one point at a time.

Frequency: For a wave, the number of complete cycles per second.

Gamma rays: Electromagnetic rays of very short wavelength, produced in radioactive decay or by collisions of elementary particles.

General relativity: Einstein's theory based on the idea that the laws of science should be the same for all observers, no matter how they are moving. It explains the force of gravity in terms of the curvature of a four-dimensional space-time.

Geodesic: The shortest (or longest) path between two points.

Grand unification energy: The energy above which, it is believed, the electromagnetic force, weak force, and strong force become indistinguishable from each other.

Grand unified theory (GUT): A theory which unifies the electromagnetic, strong, and weak forces.

Imaginary time: Time measured using imaginary numbers.

Light cone: A surface in space-time that marks out the possible directions for light rays passing through a given event.

Light-second (light-year): The distance traveled by light in one second (year).

Magnetic field: The field responsible for magnetic forces, now incorporated along with the electric field, into the electromagnetic field.

Mass: The quantity of matter in a body; its inertia, or resistance to acceleration.

Microwave background radiation: The radiation from the glowing of the hot early universe, now so greatly red-shifted that it appears not as light but as microwaves (radio waves with a wavelength of a few centimeters). Also see COBE, on page 145.

Naked singularity: A space-time singularity not surrounded by a black hole.

Neutrino: An extremely light (possibly massless) particle that is affected only by the weak force and gravity.

Neutron: An uncharged particle, very similar to the proton, which accounts for roughly half the particles in an atomic nucleus.

Neutron star: A cold star, supported by the exclusion principle repulsion between neutrons.

No boundary condition: The idea that the universe is finite but has no boundary (in imaginary time).

Nuclear fusion: The process by which two nuclei collide and coalesce to form a single, heavier nucleus.

Nucleus: The central part of an atom, consisting only of protons and neutrons, held together by the strong force.

Particle accelerator: A machine that, using electromagnets, can accelerate moving charged particles, giving them more energy.

Phase: For a wave, the position in its cycle at a specified time: a measure of whether it is at a crest, a trough, or somewhere in between.

Photon: A quantum of light.

Planck's quantum principle: The idea that light (or any other classical waves) can be emitted or absorbed only in discrete quanta, whose energy is proportional to their wavelength.

Positron: The (positively charged) antiparticle of the electron.

Primordial black hole: A black hole created in the very early universe.

Proportional: 'X is proportional to Y' means that when Y is multiplied by any number, so is X. 'X is inversely proportional to Y' means that when Y is multiplied by any number, X is divided by that number.

Proton: A positively charged particle, very similar to the neutron, that accounts for roughly half the particles in the nucleus of most atoms.

Pulsar: A rotating neutron star that emits regular pulses of radio waves.

Quantum: The indivisible unit in which waves may be emitted or absorbed.

Quantum chromodynamics (QCD): The theory that describes the interactions of quarks and gluons.

Quantum mechanics: The theory developed from Planck's quantum principle and Heisenberg's uncertainty principle.

Quark: A (charged) elementary particle that feels the strong force. Protons and neutrons are each composed of three quarks.

Radar: A system using pulsed radio waves to detect the position of objects by

measuring the time it takes a single pulse to reach the object and be reflected back.

Radioactivity: The spontaneous breakdown of one type of atomic nucleus into another.

Red shift: The reddening of light from a star that is moving away from us, due to the Doppler effect.

Singularity: A point in space-time at which the space-time curvature becomes infinite.

Singularity theorem: A theorem that shows that a singularity must exist under certain circumstances—in particular, that the universe must have started with a singularity.

Space-time: The four-dimensional space whose points are events.

Spatial dimension: Any of the three dimensions that are spacelike—that is, any except the time dimension.

Special relativity: Einstein's theory based on the idea that the laws of science should be the same for all observers, no matter how they are moving, in the absence of gravitational phenomena.

Spectrum: The component frequencies that make up a wave. The visible part of the sun's spectrum can be seen in a rainbow.

Spin: An internal property of elementary particles, related to, but not identical to, the everyday concept of spin.

Stationary state: One that is not changing with time: a sphere spinning at a constant rate is stationary because it looks identical at any given instant.

String theory: A theory of physics in which particles are described as waves on strings. Strings have length but no other dimension.

Strong force: The strongest of the four fundamental forces, with the shortest range of all. It holds the quarks together within protons and neutrons, and holds the protons and neutrons together to form atoms.

Uncertainty principle: The principle, formulated by Heisenberg, that one can never be exactly sure of both the position and the velocity of a particle; the more accurately one knows the one, the less accurately one can know the other.

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Uncertainty principle: The principle, formulated by Heisenberg, that one can never be exactly sure of both the position and the velocity of a particle; the more accurately one knows the one, the less accurately one can know the other.

Virtual particle: In quantum mechanics, a particle that can never be directly detected, but whose existence does have measurable effects.

Wave/particle duality: The concept in quantum mechanics that there is no distinction between waves and particles; particles may sometimes behave like waves, and waves like particles.

Wavelength: For a wave, the distance between two adjacent troughs or two adjacent crests.

Weak force: The second weakest of the four fundamental forces, with a very short range. It affects all matter particles, but not force-carrying particles.

Weight: The force exerted on a body by a gravitational field. It is proportional to, but not the same as, its mass.

White dwarf: A stable cold star, supported by the exclusion principle repulsion between electrons.

Wormhole: A thin tube of space-time connecting distant regions of the universe. Wormholes might also link to parallel or baby universes and could provide the possibility of time travel.

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Stephen Hawking

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ABOUT THE AUTHOR

Stephen Hawking, who was born in 1942 on the anniversary of Galileo's death, holds Isaac Newton's chair as Lucasian Professor of Mathematics at the University of Cambridge. Widely regarded as the most brilliant theoretical physicist since Einstein, he is also the author of *Black Holes and Baby Universes,* published in 1993, as well as numerous scientific papers and books.

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—*The New York Review of Books*

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